THE RELATIVE CONTRIBUTION OF HUDSON RIVER TRIBUTARIES TO RIVER HERRING SPAWNING DYNAMICS

A Thesis

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by

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ABSTRACT

Quantifying the relative tributary contribution to anadromous fish spawning dynamics is irrefutably important when prioritizing habitat enhancement, restoration and management decisions (Everly and Boreman, 1999). Collecting sound baseline data becomes critical when seeking out the most significant contributors to spawning stock and flux. Sensitivity analyses can be employed to assess the range of uncertainty as it pertains to the estimation and application of these aforementioned contributors, however, hierarchical modeling, spatio-temporal visualization, and the cross validation of estimation methods provides a suitable means for addressing this uncertainty and the associated methods required for its reduction (Sullivan and Rudstam, 2016). With consistently measured baseline data collected and uncertainty fully characterized, one can utilize parametric optimization as a mechanism for inferring wide spread population phenomena from more localized estimates (Tam *et al*., 2002).

Custom designed egg mats were deployed in Black Creek (Esopus, New York) and the Fall Kill (Poughkeepsie, New York) to obtain spawning river herring egg counts for abundance modeling and subsequent population estimation. Geographic coordinates (NAD 1983 UTM Zone 18N) were recorded at sites of egg collection, and kernel density based functions in GIS were used to visualize the spatial distribution and estimated counts of river herring throughout a given system. The sites of greatest egg deposition were ultimately viewed in conjunction with their relative proximity to the first impassable barrier to anadromous fish migration. The coordination of these activities serve to either refute or support the future augmentation of barriers to fish migration, management of habitat, prioritization of project management, and potential implementation of supplemental fish passage within tributaries of the Hudson River.

Gravid female river herring were sampled from the main stem of the Hudson River through the use of haul seines for post-mortem ovary analysis. Auto-enumeration of ovary egg contents using an Epson Perfection V19 flatbed scanner and ImageJ software allowed for fecundity analysis. Standardized river herring standing egg crop (mean egg count per female) was multiplied by female river herring population estimates, obtained from Delta Vision HD underwater camera counts and Smith-Root SR-1601 potentiometric fish counts, in order to further estimate egg productivity within a system. Delta Vision HD underwater camera daily population estimates were compared against Smith-Root SR-1601 estimates to address issues of double counting, fiscal cost, cumbrous technology, and accuracy.

BIOGRAPHICAL SKETCH

Dave Kowalik was born on February 7, 1985 and grew up in Seneca Falls, New York. He completed his first Bachelor's of Science in Marketing Management, Communications, and Music Industry at Syracuse University in 2007. Upon returning to the greater Syracuse area in 2014, he completed his second Bachelor's of Science in Aquatic and Fisheries Science and Pre Medical studies at the State University of New York College of Environmental Science and Forestry. At SUNY ESF he conducted independent honors research on *Salmo salar* and volunteered at various healthcare facilities. In 2016, Dave entered the Department of Natural Resources at Cornell University in pursuit of a Master's degree in Fishery and Aquatic Science and Quantitative Ecology. He is humbled by the opportunity to conduct novel research at a foremost research institution.

ACKNOWLEDGMENTS

I am beyond appreciative of all of the guidance and coordination that went into the completion of this research. Committee Chair Dr. Pat Sullivan has accelerated my statistical knowledge base and problem solving acuity for which I am forever grateful. More importantly however, Pat has afforded me the opportunity to conduct novel research in a field that I am passionate about, and has provided all of the tools necessary for success. I would also like to acknowledge committee member Dr. Suresh Sethi for his foresight and ingenuity in terms of sampling design, implementation and analysis. The NYSDEC Hudson River Estuary Unit was fundamental throughout the entirety of this process. The sampling effort was extremely robust, and the breadth of data procured was impressive. Specifically, I would like to thank Wes Eakin, Joe Lydon, Gregg Kenney, Amanda Higgs, Robert Adams, Rich Pendleton, Maura Grassi, Andrew Meyer and Chris Bowser.

I am indebted to Robert Schmidt and Karin Limburg whose previous Hudson River research provided much of the rationale for future study. They both made themselves accessible throughout the entirety of the process and offered highly nuanced guides and information surrounding the region. Thank you to Keith Jenkins at Cornell University for assisting with GIS based operations and also to Erika Mudrak at Cornell University for advanced coding assistance. I would like to acknowledge Ellen George for idea generation surrounding egg mat sampling design and I would like to acknowledge Ben Marcy-Quay for relevant sampling design considerations.

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Chapter 1

Introduction

Rationale for Research

With the Hudson River (New York) spanning 315 miles from its northernmost reaches of Lake Tear of the Clouds in the Adirondacks southerly to the Battery of Manhattan, deriving information on unexplored or under-sampled tributaries *a priori* from statistical based reasoning is both pragmatic and vital (Department of Environmental Conservation, 2016). A map of the Hudson River with river mile markers spanning its entirety, shows the reach of the system (Figure 1.1).

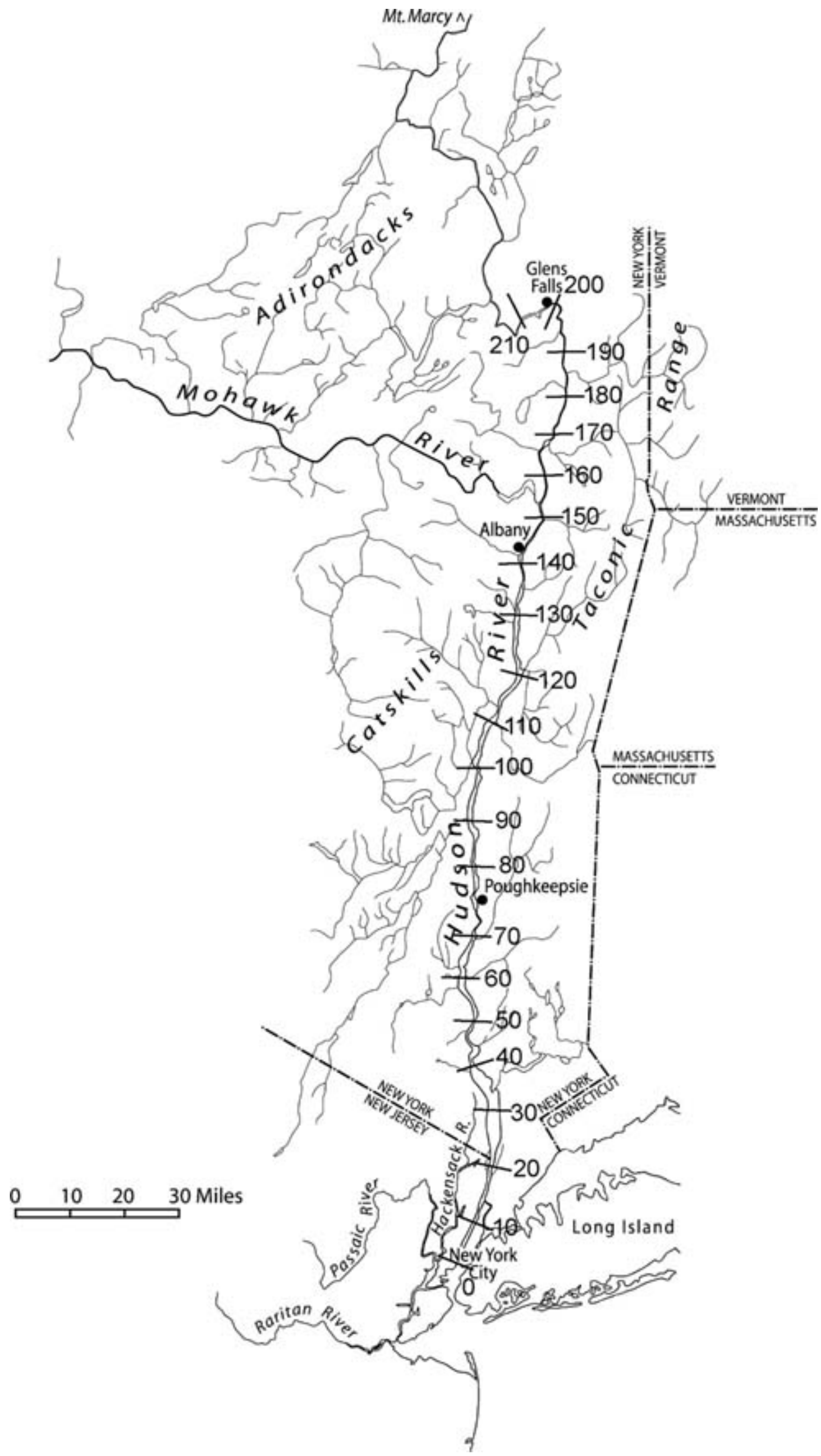

Fig. 1.1. The main stem of the Hudson River spanning from Lake Tear of the Clouds in the Adirondacks to the Battery in Manhattan. River mile markings are denoted. Map originally featured in the Journal of Environmental Toxicology and Chemistry. New York, 2008.

Stocks of blueback herring (*Alosa aestivalis*) and alewife (*Alosa pseudoharengus*), collectively known as river herring, have been of particular interest within the Hudson River and its tributaries. In 2009 the Atlantic States Marine Fisheries Commission (ASMFC) adopted amendment 2 for shad and river herring to the Interstate Fishery Management Plan. This amendment federally mandates that its member states demonstrate sustainable fisheries for river herring (ASMFC, 2009). The implementation of the Hudson River Sustainable Fishery Management Plan (SFMP) makes New York (Hudson River exclusively) one of five states with approved plans that allow directed fisheries for river herring (Hattala *et al*., 2011). This SFMP, coupled with a recent review of the ASMFC management plan for river herring (approved in May of 2016), provides the rationale for further population assessment and stock structure research within the tributaries of the Hudson River (Rootes-Murdy *et al*., 2016). Furthermore, a 2012 river herring benchmark stock assessment conducted by the ASMFC found that of 52 stocks of river herring with available data, 28 stocks could not be assessed because the time-series was too short (ASMFC, 2012). This necessitates continued long-term data collection surrounding river herring.

Tributaries of the Hudson River

Black Creek (Ulster County), and the Fall Kill (Dutchess County) are tributaries located along the Hudson River and served as the primary sites of study. The initial rationale for site selection was based on the work of Schmidt and Cooper (1996). In their report cataloging the barriers to the upstream movement of migratory fishes in the tributaries of the Hudson River, they generate a ranking system for prioritizing those tributaries that would benefit the most from augmentation of barriers to migration and/or assisted fish passage, while simultaneously documenting the location of several river herring spawning sites (Schmidt and Cooper, 1996). Black Creek, and the Fall Kill are relatively high priority tributaries considered significant for further study (Schmidt and Cooper, 1996). Though the Fall Kill doesn't rank as highly as Black Creek, the unknown status of the herring run serves to diminish its potential ranking (Schmidt and Cooper, 1996). This justifies further river herring population study as well as an update of overall tributary condition. Given that the Fall Kill is similar in size to Black Creek, it also warrants further examination to create a spawning dynamics index for tributaries of comparable size.

These sites were assessed further and were ultimately chosen based on several in-person survey observations and criteria. Black Creek (~2.4m wide at Winding Brook Rd.) and the Fall Kill (~2.0m wide at North Water St.) represent smaller systems and were chosen for comparison with tributaries of similar width, depth, size and overall physiography. In regards to location, these sites are contained within Ulster and Dutchess County and span an 8.18 river mile distance. This relatively close proximity allowed for the synchronization of data measurements, and coordination of personnel in the field. Furthermore, this focused river mile distance may prove useful for creating accurate indices attributable to surrounding areas, and for comparing abundance estimates in neighboring locations.

Accessibility and navigability were also major considerations influencing the selection of these two sites. Black Creek and the Fall Kill are accessible via wading for weir and camera installation, monitoring and maintenance of the Smith-Root fish counter (automatic enumeration), as well as drift net and egg mat deployment. The NYSDEC Hudson River estuary program has conducted river herring studies in these areas in addition to a host of other surveying endeavors.

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Chapter 2

N-Mixture Modeling of River Herring Egg Abundance and Distribution in the Tributaries of the Hudson River

Abstract

N-mixture models are often employed to estimate latent organismal abundance while concurrently accounting for detection probability (Kéry and Royle, 2016). Our study offers a novel means for simultaneously measuring abundance, detection probability and gear efficiency by focusing on a previously under studied and relatively immobile subject (river herring eggs). Custom designed egg mats, accommodating two individual 30.5cm x 40.6cm (12” x 16”) collecting surfaces were deployed in the Fall Kill and Black Creek (tributaries of the Hudson River in New York) to collect river herring eggs during spawning season. Mats were orientated approximately parallel to stream flow under a stratified random sampling design over the course of the spawning period. This allowed for an assessment of the spatial distribution of eggs over time. Strata were defined as three equidistant spatial segments measured from a given tributary’s confluence with the main stem of the Hudson River to the first impassable barrier to fish migration. Ninety-three total sites were surveyed (48 sites in Black Creek, and 45 sites in the Fall Kill) with the majority of eggs being detected within the upper 2/3rds of each respective tributary. Throughout the course of the sampling season, an average of 1,595 eggs per egg mat subsampling event were recovered from the upper two strata of Black Creek, and an average of 2,619 eggs were recovered from the upper two strata of the Fall Kill. With tributaries combined, an egg density of 895 eggs per $58.1cm^2$ (3” x 3”) egg mat subsample was observed over an

average deployment duration of 3.8 days, with a detection rate of 87%. The most upstream egg mat surface collected a greater number of eggs throughout the season with a mean abundance of 992 eggs. The N-mixture negative binomial model outperformed Poisson and zero-inflated Poisson N-mixture models using AIC. Standard generalized linear models that assume 100% detection probability, under predicted egg abundance relative to the N-mixture model. N-mixture modeling using the *unmarked* (Fiske and Chandler, 2011) package in R proved to be more efficient in terms of iteration processing time when compared to Bayesian based hierarchical modeling processed through the *jagsUI* (Kellner, 2016) package (Meehan *et al*., 2017).

Introduction

N-mixture modeling is commonly used by ecologists interested in measuring organismal abundance while accounting for detection uncertainty (Kéry and Royle, 2016). An aquatic based N-mixture model study of smallmouth bass (*Micropterus dolomieu*) in Oklahoma relied upon 48 hour electrofishing intervals to note the presence and abundance of smallmouth bass per a variable area of observation (Mollenhauer and Brewer, 2017). Data collection under this type of design is subject to temporal variation as one experiences delayed observation between electrofishing events, and is also prone to spatial variation as the observation area becomes larger and less certain. When applied to mobile adult fish species in dynamic aquatic systems, one traditionally has to account for a more rapid flux of site occupancy by individuals in a given population. Additional applications of N-mixture modeling in aquatic systems encounter further challenges such as the disturbance of the intended study species, as well as environmentally dictated and potentially compromised regions (e.g. increased turbidity, and limited access) of habitat for data collection (Som *et al*., 2017). In reducing the area over which the observations are taken, and in making simultaneous observations of a stationary egg's site occupancy, the potential for reduced spatial and temporal variation, mitigation of species disturbance, and flexibility in study site selection becomes feasible. The *unmarked* (Fiske and Chandler, 2011) package in R, and the Bayesian based *jagsUI* (Kellner 2016), are two statistical options for employing hierarchical models and we compare model performance using both (Meehan *et al*., 2017).

In addition to modeling abundance, characterizing the spatial distribution of a species over time provides a useful method for explaining in-river behavior. This behavior may in turn be useful for applied fisheries management and decision-making. Specifically, knowing which portion of a tributary is inhabited by spawning fish may allow for a more concerted habitat enhancement, restoration and protection effort (Everly and Boreman, 1999). In discussing the barriers to upstream migration of migratory fish in Hudson River tributaries, Schmidt and Cooper (1996) create a ranking system for prioritizing habitat and barrier augmentation potential, using criteria such as water quality, estimated river herring run potential and tributary size. Coupling the estimated population size of a river herring run with the knowledge of whether or not spawning takes place, will reaffirm or refute the added costs and benefits of manipulating barriers or implementing supplemental fish passage.

The Fall Kill and Black Creek tributaries are of particular importance for river herring in the Hudson River watershed, but data on habitat effects and spawning dynamics are limited. Black Creek falls within the top ten tributaries that are of highest priority for barrier augmentation or implementation of methods to promote additional fish passage (Schmidt and Cooper, 1996). In contrast, the Fall Kill has been identified as an under studied tributary with relatively unknown river herring spawning potential (Schmidt and Cooper, 1996). The rationale for prioritization of habitat enhancement on the Fall Kill is diminished due to the fact that river herring spawning potential has been undocumented, the tributary has had historically high anthropogenic inputs, and because of the associated complexity involved with implementing supplemental fish passage (Schmidt and Cooper, 1996). A better understanding of the abiotic factors currently influencing river herring spawning habitat, will serve to update and expand upon this literature. The work presented here, by focusing on a high priority tributary such as Black Creek and a classically under studied tributary in the Fall Kill, will allow for a broader assessment of river herring spawning potential and will create an opportunity for collecting novel insight.

River Herring Biology

Blueback herring (*Alosa aestivalis)* and alewife (*Alosa pseudoharengus)* exhibit overlap in their geographic distributions, with the former ranging from New Brunswick to the St. Johns River in Florida and the latter from Newfoundland to North Carolina (McBride *et al*., 2010). Loesch (1987) described this sympatric overlap as occurring between New Brunswick and upper South Carolina a few decades earlier. Loesch (1987) also notes that blueback herring utilize lentic flows for spawning outside of this sympatric range, but may be relegated to more realized lotic flows in areas shared with alewife. Regardless of the spatial range that these two species occupy, alewife tend to be found deeper in the water column of a given system (Loesch, 1987).

As anadromous fish, river herring use estuarine tributaries for spawning habitat (Schmidt and Limburg, 1989; Schmidt and Stillman, 1994). Alewife and blueback herring are defined as mature between ages three to eight and ages three to six, respectively, at which point they migrate downstream post spawn (Atlantic States Marine Fisheries Commission, 2016). Juveniles of both species remain in freshwater nursery areas in spring and early summer, but may also move upstream in the presence of higher salinity (Atlantic States Marine Fisheries Commission, 2016). As water temperatures decline in the fall, juveniles move downstream to waters of greater salinity (Atlantic States Marine Fisheries Commission, 2016).

Though morphologically similar, adult alewife can be distinguished from blueback herring through the examination of body depth. Adult alewife possess a deeper body characterized by a comparatively greater circumference at the rostral 1/3rd. The eye diameter of adult alewife is often larger than the gap between the tip of the snout and the front margin of the eye, whereas the eye diameter of blueback herring is comparable to this gap (Loesch, 1987). Internally, the peritoneum of adult blueback herring is typically darker in color than its counterpart (Loesch, 1987). The iridescent blue dorsal coloration of blueback herring, when viewed within the water column, is attributable to its shallower vertical distribution (27-55m) where blue light subsequently penetrates the column before attenuation (Neves, 1981). Alewife have a more greenish dorsal coloration when observed in the water column (56-110m) due to a greater penetrance of green light (Neves, 1981).

Ecologically, river herring play a substantial role in nutrient cycling as they redistribute nutrients from freshwater to marine environments (Mullen *et al.,* 1986). The diets of both species consist primarily of zooplankton (e.g. *Urytbmora affinis*), however fish eggs, crustacean eggs, insects, insect eggs, and small fish may be of dietary importance (Bigelow and Schroeder, 1953). As forage, both species are prey to piscivorous fish including striped bass (*Morone saxatilis*), and aerial predators such as terns and gulls (Mullen *et al*., 1986).

Abiotic Factors

Bimodal spawning has been noted in several Hudson River tributaries (Schmidt and Limburg, 1989; Schmidt and Stillman, 1994). Alewife is believed to be the predominant tributary spawner as evidenced by a temporal spawning separation of one to two weeks (Schmidt and Cooper, 1996). Several abiotic factors have been studied in an effort to distinguish spawning site preference and behavior between these two species collectively known as river herring, but few have been linked to river herring in the tributaries of the Hudson River. In 1977, Loesch and Lund surmise that blueback herring prefer spawning sites with strong currents and hard substrates while alewife are more opportunistic generalists. Similarly, Richkus (1974) claims that light intensity and changes in water temperatures strongly influence the timing of upstream movement among alewife individuals. Richkus (1974) also noted that downstream movements during the summer and fall were inhibited by a sunlight and shade interface present at a highway bridge. He describes a scenario where more fish passed under a certain bridge on cloudy days rather than on sunny days (Richkus, 1974).

Kellogg (1982) reported an upper lethal temperature of 29.7 degrees C for alewife eggs procured from the Hudson River and reared at a bioassay laboratory located at the Roseton Generating Station. A temperature of 20.8 degrees C appeared to be optimal for maximizing hatching success (Kellogg, 1982). Maximum net biomass gained by larval alewife occurred at 26.4 degrees C (Kellogg, 1982).

Hatching and juvenile river herring preference studies have also taken abiotic factors such as chemical aquatic composition into account. Young-of-the-year alewife and blueback herring from the Cape Fear River, North Carolina, were found to be abundant in water where free carbon dioxide ranged from 4-22ppm, alkalinity from 5-32ppm, dissolved oxygen from 2.4-10.0ppm, and pH from 5.2-6.8 (Davis and Cheek, 1966).

Hypotheses

Several abiotic factors were studied in conjunction with the early developmental success of alewife reared from the Hudson River (Kellogg, 1982). Few, however, attempt to quantify spawning river herring abundance and egg productivity within the tributaries of the Hudson River as a function of abiotic habitat factors. Our research aims to attribute expected egg abundance to measurably comparable abiotic variable levels amongst these tributaries. The purpose is ultimately to create an index for predicting future in-stream spawning population dynamics.

Based on previous habitat suitability index studies, it is my belief that the greatest abundance of river herring eggs will be counted at sites exhibiting temperature ranges between 12-16 degrees C (Pardue, 1983). In terms of stream flow, the greatest number of river herring eggs will be noted in flows between 0-1m/s (Pardue, 1983). Based on the luminosity research of Richkus (1974), I also estimate that the greatest number of river herring eggs will be found during moon phase percentages of less than 50%.

Methods

River Herring Egg Abundance, Site Occupancy, and Gear Efficiency

River herring egg and larval abundance, as well as eggs from other species, were measured at both Black Creek and the Fall Kill. The sampling period occurred from April 17, 2017 to June 05, 2017 corresponding with known river herring spawning runs (Limburg and Schmidt, 1990). Both of our study sites were divided into three equal sampling sections based on total length from the Hudson River main stem interface to each respective tributary's first barrier. A historically documented first barrier of Black Creek consisted of a broken dam located behind (west) the Ascension Cemetery on rt. 9W (1.8km upstream (south west) of the Hudson River interface)(Schmidt and Cooper, 1996). On-site observations revealed that this barrier no longer prohibits river herring passage and a new barrier has since been documented in all DEC barriers online inventories (Figure 2.1).

Fig. 2.1. Photo of the updated first barrier located upstream of the Black Creek and Hudson River confluence. This natural waterfall was discovered near the Town of Esopus Transfer Station and has since been updated in relevant online barriers inventories. New York, 2017.

The first barrier of the Fall Kill consists of a set of natural falls located 0.15km upstream of the Hudson River confluence (Figure 2.2).

Fig. 2.2. Photo of the first barrier located upstream of the Fall Kill and Hudson River confluence. This barrier consists of a set of gradually sloping waterfalls. New York, 2017.

Alewife eggs have been shown to hatch anywhere from two to three days at 22 degrees C, three to five days at 20 degrees C and about six days at 15.6 degrees C (Bigelow and Schroeder, 1953). Blueback herring eggs hatch from three to four days at 20-21 degrees C and 55-58 hours at 22.2-23.7 degrees C (Bigelow and Schroeder, 1953). With these durations noted, egg and larval sampling events were conducted in weekly intervals so that recently hatched larva would be accounted for.

Custom built egg mats were deployed for egg productivity estimation and further gear feasibility study in the Fall Kill and Black Creek (Figure 2.3).

Fig. 2.3. Photo of a single egg mat unit housing two collecting surfaces comprised of furnace filter material. The collecting surfaces were fastened to sand filled PVC piping with zip ties and the entire mat was braced with rebar. New York, 2017.

Two 30.5cm x 40.6cm (12” x 16”) furnace filter rectangles were fastened to a custom constructed PVC frame (three sets of two mats fastened with zip ties to PVC frames filled with sand for added weight). This design is based on the egg collection device implemented by Nichols (2003) in a study of lake sturgeon (*Acipenser fulvescens*). One unit, consisting of two mats, was placed in each of the three strata of the Fall Kill and each of the three strata of Black Creek per a given time interval. Egg mats were checked simultaneously with drift net events and also at random times during equipment maintenance visits. A random geographic coordinate selector was utilized in ArcGIS to generate sample locations for egg mat deployment. Figure 2.4

illustrates an potential egg mat deployment site in the Fall Kill and Figure 2.5 highlights the location of similar sites for Black Creek.

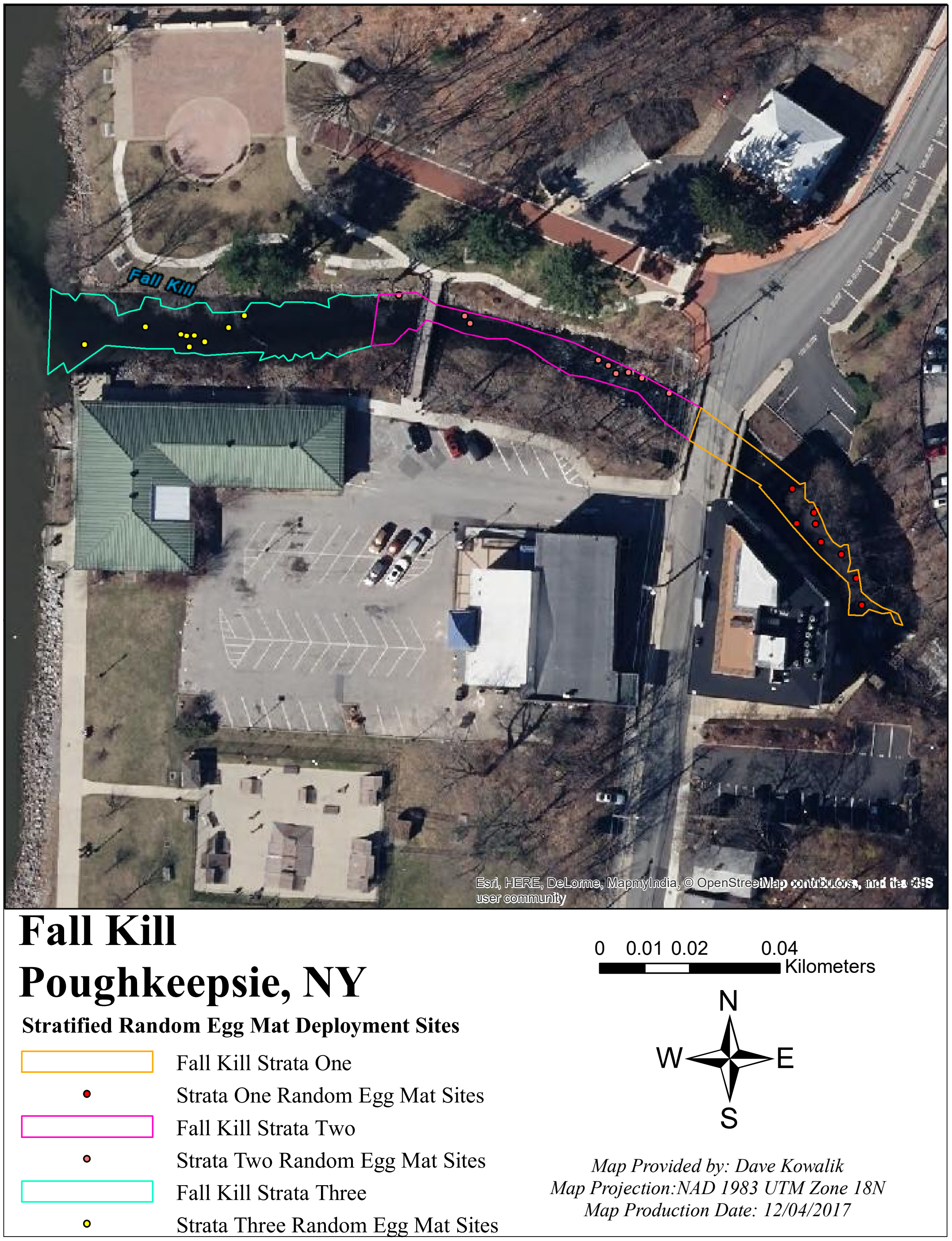

Fig. 2.4. Randomly generated egg mat deployment locations within the three strata of the Fall Kill. Points were created using ArcGIS. New York, 2017.

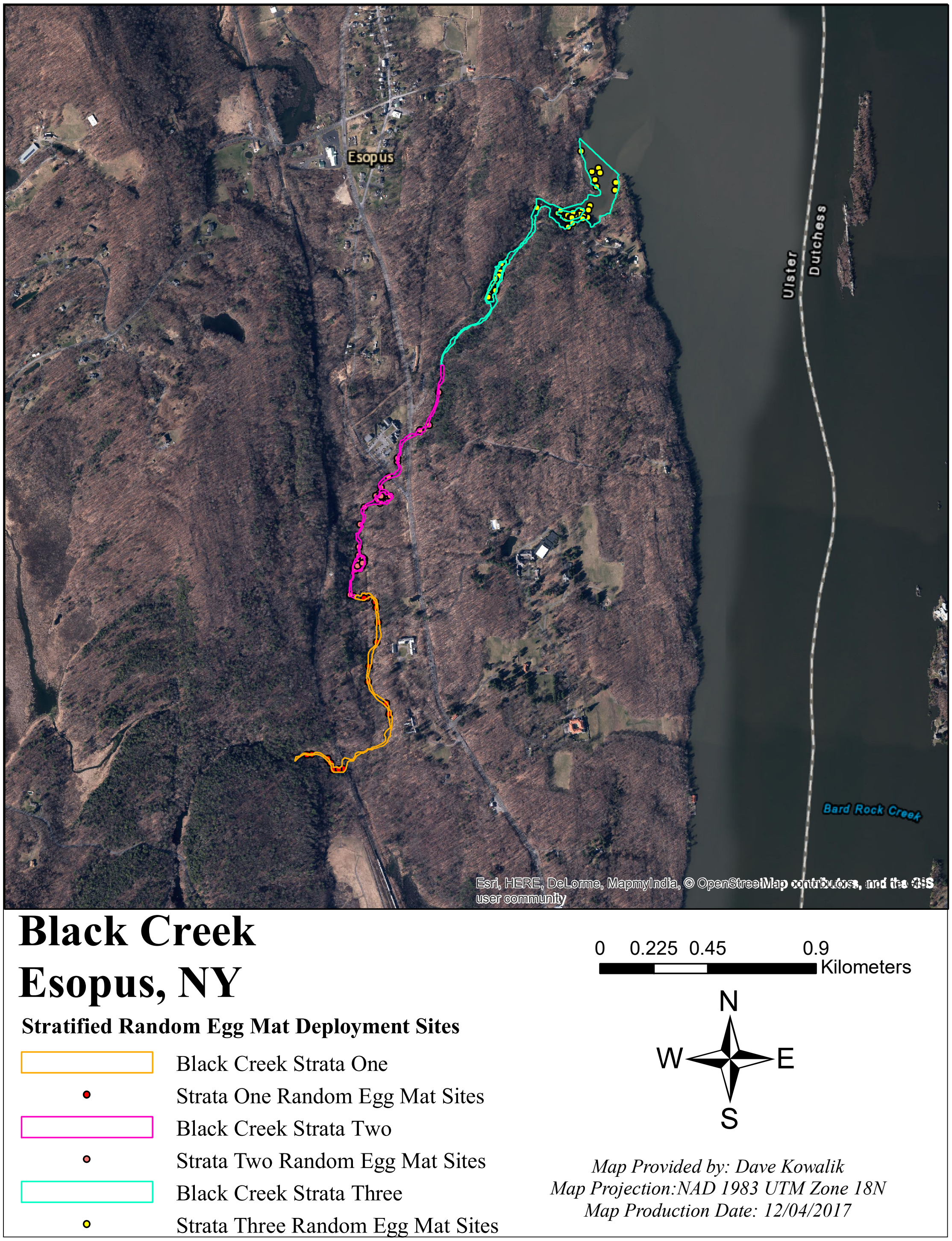

Fig. 2.5. Randomly generated egg mat deployment locations within the three strata of Black Creek. Points were created using ArcGIS. New York, 2017.

These mat sets, oriented approximately parallel to the flow of the stream, facilitated analysis using occupancy modeling to derive estimates of abundance and detection probability. This approximately parallel orientation served to reduce the impact of increased flows. The egg mats were fastened to the riverbed with rebar in order to preserve their orientation and location. A $58.1cm^2$ (3" x 3") area of egg mat was subsampled according to a simple random sampling design (Figure 2.6).

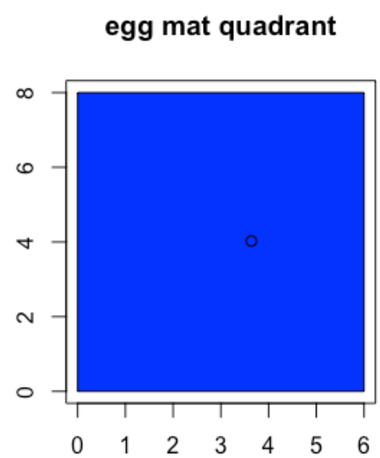

Fig. 2.6. Randomly generated egg subsampling location. A uniform random number generator was configured in R and the circle within the egg mat quadrant corresponds with the location of a $58.1cm^2$ square to be subsampled. New York, 2017.

These egg mat subsamples, along with their collected egg and larval contents, were placed in a whirl-pak and stored in 95% EtOH for later counting (Lake and Schmidt, 1998). Alewife eggs are about 1.27mm in diameter, pink, demersal and adhesive whereas blueback herring eggs are about 1.00mm in diameter, and are adhesive as well (Bigelow and Schroeder, 1953). This egg color and size aided in the initial discernment between river herring and non-river herring species, and the egg mat furnace filter material offered a suitable ground for egg adhesion.

A 500µm fine mesh sieve was used in the lab to filter the egg and larval contents from the associated egg mats and debris. These remaining contents were placed in a Pyrex petri dish and were separated, identified and hand enumerated under a dissecting microscope. The number of river herring eggs, river herring larva, and eggs of other species were recorded.

A YSI multi-parameter water quality sonde, and flow meter were deployed next to egg mats in-stream to document the abiotic factors potentially influencing egg habitat. Observers positioned themselves to the side of an egg mat and in a manner as to not obstruct the incoming flow of eggs and water when recording observations. The GPS coordinates (NAD 1983 UTM Zone 18N) were recorded for each egg mat location through the use of Garmin handhelds and converted to decimal degree in ArcGIS. These coordinates were ultimately used for geospatial analysis of river herring egg concentrations.

A series of N-mixture based hierarchical models and a corresponding set of generalized linear models (GLM's) were explored in the estimation of river herring egg abundance as a function of quantitative abiotic covariates. All abundance calculations were conducted on a per subsample basis and later extrapolated to the entire bottom surface area of each tributary. N-mixture model analysis was applied by using the *unmarked* (Fiske and Chandler, 2011) package in R. This facilitated model comparison with GLM's using AIC (Sakamoto *et al.,* 1986). N-mixture hierarchical models specifically estimated river herring egg abundance while simultaneously accounting for detection probability. The structure of the N-mixture model consists of a state process (abundance) and observational process (detection probability)

1.) State Process: $N_{(i)} \sim NegBinom(\lambda, \omega)$

2.) Observational Process: $C_{ij}|N_i \sim Binomial(N_{i,}p)$

where N_i is the latent abundance at site i (i = 1,…,M), λ is the mean expected abundance over all sites, and ω is the overdispersion parameter, C_{ij} is the count at site i during survey j (j=1,…,J), and p is the detection probability across all individuals (Kéry and Royle, 2016). A negative binomial distribution is depicted for the state process in the previous equation, however, Poisson and zero-inflated Poisson distributions were also explored.

For comparison, a GLM was also applied. GLM's similarly model abundance from count data, however in their simplest form, they do not account for imperfect detection probability. Their structure is additive and linear in terms of parameters, though with a log link function under a count based distribution assumption which does not necessarily result in straight-line relationships. With our count data, a distribution other than normal is assumed and thus the effect of predictive covariates is expressed through a transformation (link function) of the expected linear response (Kéry and Royle, 2016). The GLM is defined as

$$y_i \sim f(\theta)$$

$$g(E(y_i)) = \alpha + \beta * x_i$$

where y denotes a response variable following a distribution f with parameter(s) θ, and the transformed g of the expected response is a linear function of the covariates (Kéry and Royle, 2016). With negative binomial distribution, the link function results in a log transformation of the expected count value which is represented as

$$C_i \sim NegBinom(\lambda_i, \omega)$$

$$\mathrm{Log}(\lambda_i) = \alpha + \beta * x_i$$

where the response variable C_i follows a negative binomial distribution with a mean response λ_i, an overdispersion parameter of ω and the two parameters of α and β of the log linear regression of counts on designated predictor value(s) is defined (Kéry and Royle, 2016). Poisson and zero-inflated Poisson distributions were also explored here.

Spatial Distribution

The number of river herring eggs at a deployed egg mat site was recorded along with the associated latitude and longitude. In terms of spatial reference, our sites fall within the projected coordinate system NAD 1983 UTM zone 18N. By looking at the egg abundance spatially over time, we were able to visualize the spatial distribution of eggs throughout the sampling season. The earlier dates of the herring run could be viewed in association with later dates, to locate ideal egg habitat over a time series. ArcGIS was used to plot these points of varying egg concentrations and kernel density smoothers were used to project estimated counts to areas of likely observation.

The kernel density spatial analysis tool (Beyer, 2004) in ArcGIS was used to create a heat map of herring egg concentrations and predicted egg counts. This kernel based method estimates density as a sum of ‘bumps’ centered at the loci of observations, and ArcGIS can be used to estimate counts by raster (Silverman, 1998). The multivariate kernel density estimator is denoted as

$$\hat{f}(x) = \frac{1}{nh^d} \sum_{i=1}^{n} \mathrm{K}\left\{\frac{1}{h}\,(\mathrm{x} - \mathrm{X}_i)\right\}$$

in which K is the kernel, *h* is the window width smoothing parameter, and *d* is the dimension of x (Silverman, 1998). In our application for dimensional spheres where *d*=2, we applied the kernel

$$K_2(\mathrm{x}) = \begin{cases} 3\pi^{-1}\,(1 - \mathbf{x}^{\mathrm{T}}\mathbf{x})^{\mathbf{2}} & \text{if}\, \mathbf{x}^{\mathrm{T}}\mathbf{x} \ < 1 \\ 0 & \text{otherwise} \end{cases}$$

for its differentiability characteristics and quick computation time (Silverman, 1998). An empirical semivariogram was initially examined for potential Kriging based estimation of egg count, however, a pure nugget effect indicated a lack of spatial autocorrelation.

Results

River Herring Egg Abundance, Site Occupancy, and Gear Efficiency

The Fall Kill and Black Creek tributaries were surveyed with 45 sites being sampled in the Fall Kill and 48 sites in Black Creek. Daily river herring egg counts, obtained from $58.1cm^2$ egg mat subsamples, for both the Fall Kill and Black Creek combined were calculated from April 17, 2017 to June 5, 2017 (Figure 2.7).

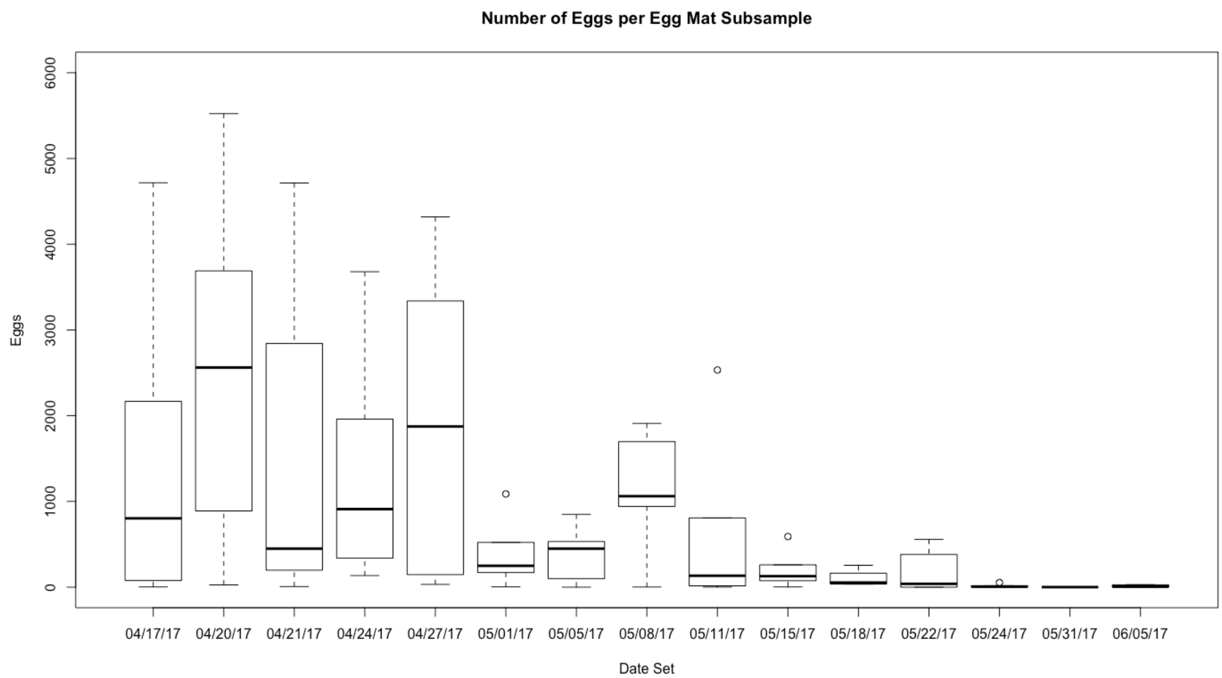

Fig. 2.7. Box and whisker plot of river herring eggs collected from Black Creek and Fall Kill egg mat subsamples combined. $58.1cm^2$ egg mat subsamples were surveyed throughout the sampling season. New York, 2017.

The average egg mat deployment duration was 3.8 days. The average abundance of river herring eggs per the average duration, per egg mat subsample, over the course of the sampling season was 895 eggs. A paired-sample t-test revealed that the mean river herring eggs collected with the upstream oriented collecting surface was significantly different from the downstream surface (p

= .04) with a mean difference of 192 eggs. The average abundance of river herring larva per the same subsampling dimensions and durations was also noted (Figure 2.8).

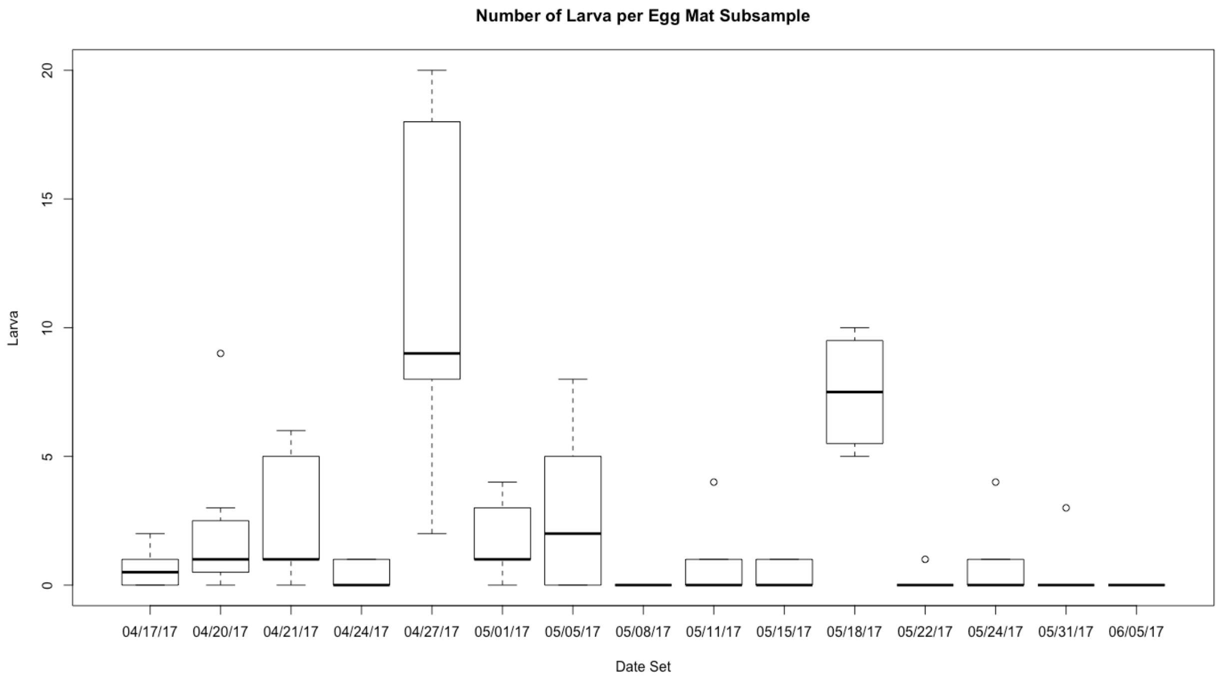

Fig. 2.8. Box and whisker plot of river herring larva collected from Black Creek and Fall Kill egg mat subsamples combined. 58.1cm^2 egg mat subsamples were surveyed throughout the sampling season. New York, 2017.

The average abundance of river herring larva per the aforementioned average duration, per egg mat subsample, over the course of the sampling season, was two larva. The average abundance of eggs identified as other species, per the average duration, and same egg mat subsample, over the course of the sampling season was found to be 72 eggs. Other species eggs were identified predominantly as white perch (*Morone americana*) and white sucker (*Catostomus commersonii*) eggs. A compiled field guide to Hudson River tributary larval fish and eggs was used to identify genera and species (Schmidt, 2017). Dissecting microscope images of river herring eggs and yolk-sac larva are provided (Figure 2.9).

Fig. 2.9. River herring egg and yolk-sac larva obtained from egg mat samples. River herring eggs are approximately 1-1.27mm in diameter. Yolk-sac river herring larva are identified by their long and slender caudal section. New York, 2017.

In considering Black Creek individually, an average abundance of 568 river herring eggs per egg mat subsample was recorded over an average duration of 3.7 days. An average abundance of two river herring larva, and 11 eggs of other species were found under the same conditions. In regards to the Fall Kill, the average egg mat deployment duration was 3.9 days. Barring any changes to the other sampling parameters, river herring egg abundance was 1,222 eggs per egg mat subsample, river herring larval abundance was two larva, and the eggs of other species was 138 eggs.

The mean number of river herring eggs, larva and the eggs of other species (per subsample) were recorded per strata for Black Creek (Table 2.1)

Table 2.1. River herring eggs, larva, and the eggs of other species are recorded for Black Creek. These are mean values per egg mat subsample. New York, 2017.

Strata Number	River Herring Eggs	River Herring Larva	Eggs of Other Species
1	497	2	3
2	1088	2	23
3	215	1	7

The greatest number of river herring eggs were recovered in the central strata. Similarly, the mean number of river herring eggs, larva, and the eggs of other species (per subsample) were also recorded per strata for the Fall Kill (Table 2.2).

Table 2.2. River herring eggs, larva, and the eggs of other species are recorded for the Fall Kill. These are mean values per egg mat subsample. New York, 2017.

Strata Number	River Herring Eggs	River Herring Larva	Eggs of Other Species
1	1110	2	103
2	1509	3	225
3	1086	1	84

Again, the greatest number of river herring eggs were found in the central strata.

The number of river herring eggs found at moon phase percentages less than 50% was equal to 53,729, and the number of river eggs found at moon phase percentages greater than 50% was 29,462. The number of river herring eggs found at water temperatures between 12-16 degrees C was 838 eggs, between 13-17 degrees C was 1,051 eggs, between 14-18 degrees C was 838 eggs, between 15-19 degrees C was 811 eggs, between 16-20 degrees C was 461 eggs, and between 17-21 degrees C was 242 eggs. The number of river herring eggs found at water velocities between 0-1m/s was 15,173 eggs, between 1-2m/s was 32,060 eggs, and between 2-3 m/s was 45,746 eggs.

River herring egg count predictor covariates were initially inspected visually using a correlogram. This process was explored for both tributaries combined. The date an egg mat was set was converted to Julian date to create a continuous predictor covariate. Air temperature was found to be significantly correlated with water temperature (positive association), and the associated correlogram visually illustrates this multicollinearity (Figure 2.10).

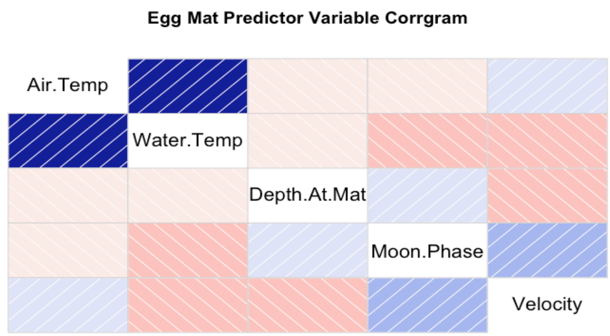

Fig. 2.10. The associated correlogram shows correlations between predictor variables. Blue coloration signifies a positive correlation and red signifies the antithesis. Darker values denote stronger associations. New York, 2017.

Air temperature was removed from subsequent models to avoid spurious results as water temperature was deemed more significant for describing river herring egg habitat. A numeric correlation plot shows the significant predictor variables used for modeling river herring egg abundance as a function of habitat (Figure 2.11).

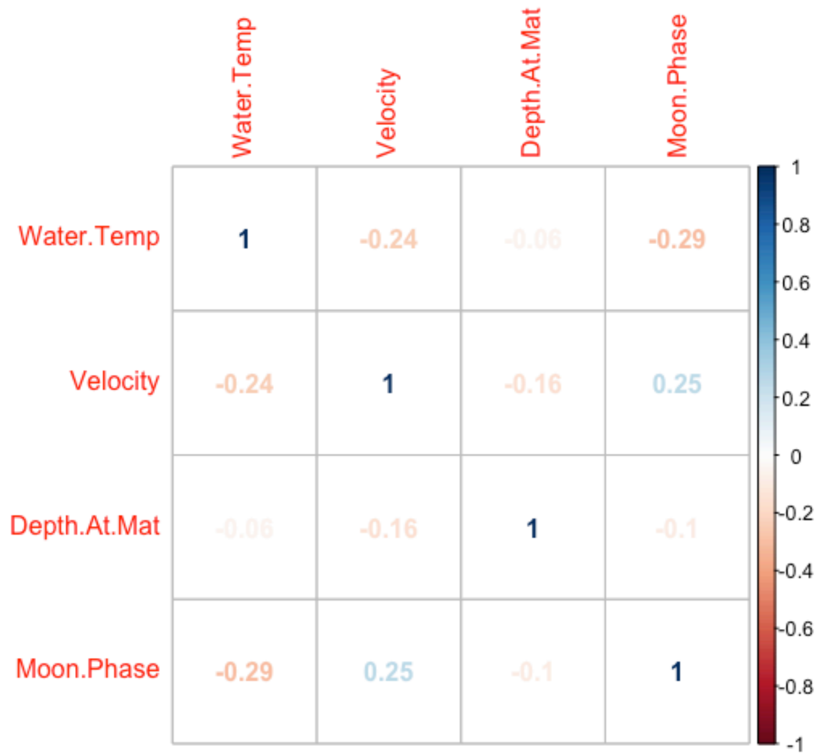

Fig. 2.11. A numeric correlation plot describing the relationship between predictor variables. Air temperature has been removed from further analysis due to issues of multicollinearity. New York, 2017.

GLMS's, N-mixture models, and related hierarchical models were explored to model river herring egg abundance as a function of numeric-based abiotic predictor variables. Egg mat deployment duration and its potential offset were omitted from subsequent models as the number of eggs recovered did not show a significant linear relationship with the amount of time an egg mat collecting device was deployed. The best fitting GLM, following a negative binomial distribution, was chosen based on AIC model comparison criteria (Table 2.3).

Table 2.3. Generalized linear model explored at both Black Creek and the Fall Kill tributaries combined. The negative binomial distribution resulted in the best fitting model. New York, 2017.

Variable	Estimate	Std. Error	z value	Pr(>|z|)	Sig. Code
(Intercept)	12.842	1.818	7.065	<0.001	***
Water Depth	-0.021	0.011	-1.966	0.049	*
Water Velocity	0.876	0.182	4.801	<0.001	***
Moon Phase	-0.018	0.006	-3.003	0.003	**
Water Temperature	-0.403	0.101	-3.985	<0.001	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

The null deviance was 146.16 on 92 degrees of freedom, and the residual deviance was 118.27 on 88 degrees of freedom. Moon phase (low light), water temperature (cooler temperatures), water depth (shallower depths), and water velocity (greater velocities) appear to have significant effects on increased river herring egg observations (when collecting eggs with egg mats).

Bayesian based hierarchical models and N-mixture hierarchical models were initially compared side-by-side to determine their ability to predict river herring egg abundance sans predictor covariates. The λ parameter was set to 895 and the probability of egg mat egg detection was 87.0% for both Black Creek and the Fall Kill combined. The Bayesian approach yielded a river herring egg abundance estimate of 945 eggs with a detection probability estimate of 82%, and the N-mixture approach resulted in 912 eggs with a detection probability of 85% (Table 2.4).

Table 2.4. N-mixture model and Bayesian hierarchical model simulations used to calculate egg abundance and egg mat probability detection rates. New York, 2017.

Model	Measure	Estimate	SE	Index	Index Value
N-mixture	Abundance	912	11.500	AIC	1661.641
	Detection Probability	0.852	0.010		
Bayesian	Abundance	945	12.442	DIC	1647.070
	Detection Probability	0.823	0.028		

Initial hierarchical model performance proved similar, however, N-mixture hierarchical modeling was chosen for future modeling of river herring egg abundance against abiotic explanatory variables because of its comparable AIC model indexing properties, lower standard error values, and faster computing time.

In both Black Creek and the Fall Kill combined, N-mixture models with Poisson, negative binomial, and zero-inflated Poisson distributions were compared for model performance using AIC. The Poisson family of distribution had an AIC of 64,870.60, negative binomial was 28,471.33, and zero-inflated Poisson was 62,878.43. A goodness of fit test revealed a $\hat{c}$ value of 1.11 for the better fitting negative binomial N-mixture model. The best fitting negative binomial model is represented (Table 2.5).

Table 2.5. N-mixture model abundance estimates (log-scale) reported as a function of water depth, and detection probability estimates (logit-scale) reported as a function of water velocity. The state and observational model are explored simultaneously in this hierarchical model. Negative binomial regression models showed significantly lower AIC index values. New York, 2017.

Measure	Variable	Estimate	Std. Error	z value	Pr(>|z|)	Index	Index Value
Abundance	(Intercept)	7.461	0.477	15.640	<0.001	AIC	28471.330
	Water Depth	-0.009	0.011	-0.820	0.412		
Detection Probability	(Intercept)	0.005	0.019	0.270	0.787		
	Water Velocity	-0.267	0.010	-26.44	<0.001		

The predict function was used to estimate river herring egg abundance and detection probability per the covariates of this N-mixture model under a 95% confidence interval (Table 2.6).

Table 2.6. The predict function was used in conjunction with the stored (data frame) N-mixture abundance covariate predictor as well as the detection probability covariate predictor to estimate the predicted lambda and detection probability values (respectively). New York, 2017.

Covariate	Water Depth/Velocity Value	Predicted Abundance/Detection Probability Value	SE	Lower	Upper
Water Depth	40(cm)	1198	254	791	1816
	50(cm)	1092	275	666	1789
Water Velocity	0.25(m/s)	48.45%	0.004	47.65%	49.26%
	0.50(m/s)	46.79%	0.003	46.08%	47.50%

The GLM (negative binomial distribution), and N-mixture hierarchical model (negative binomial distribution), for both tributaries combined, were then plotted side by side (Figure 2.12).

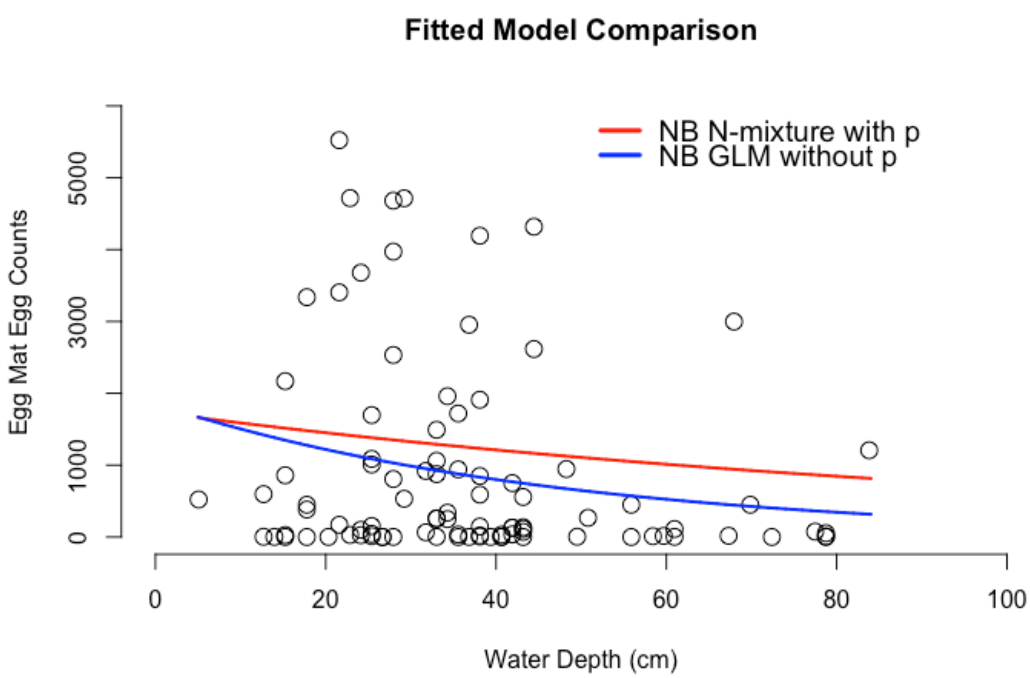

Fig. 2.12. Estimated river herring egg mat egg counts per $58.1cm^2$ subsample, fit with generalized linear model, and N-mixture model lines against water depth. The negative binomial (NB) N-mixture model considers probability detection (p) as a function of water velocity. New York, 2017.

The negative binomial N-mixture hierarchical model predicted higher egg mat egg counts on average when compared to the GLM following negative binomial distribution.

GLM's, and N-mixture hierarchical models were also used to analyze river herring egg abundance for Black Creek independently. A GLM (negative binomial) with water velocity, Julian date set, and water temperature covariates proved to be the best fitting GLM in this instance (Table 2.7).

Table 2.7. Generalized linear model explored at Black Creek. The negative binomial distribution resulted in the best fitting model. New York, 2017.

Variable	Estimate	Std. Error	z value	Pr(>|z|)	Sig. Code
(Intercept)	516.321	294.468	1.753	0.079	.
Water Velocity	1.300	0.207	6.292	<0.001	***
Julian Date Set	-0.030	0.172	-1.722	0.085	.
Water Temperature	-0.268	0.017	-1.964	0.049	*

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

The null deviance was 99.284 on 47 degrees of freedom while the residual deviance was 58.617 on 44 degrees of freedom. Increased velocities, earlier dates in the season, and colder water temperatures were linked to increased egg productivity. The N-mixture (negative binomial) model estimating abundance as a function of water temperature and detection probability as a function of water velocity was the best fitting hierarchical model at Black Creek (Table 2.8).

Table 2.8. N-mixture model abundance estimates (log-scale) reported as a function of water temperature, and detection probability estimates (logit-scale) reported as a function of water velocity. The state and observational model are explored simultaneously in this hierarchical model. The negative binomial regression model showed significantly lower AIC index values for Black Creek. New York, 2017.

Measure	Variable	Estimate	Std. Error	z value	Pr(>|z|)	Index	Index Value
Abundance	(Intercept)	11.404	2.170	5.270	<0.001	AIC	9246.544
	Water Temperature	-0.291	0.140	-2.080	0.038		
Detection Probability	(Intercept)	-1.351	0.063	-21.590	<0.001		
	Water Velocity	0.213	0.022	9.910	0.037		

The GLM (negative binomial distribution), and N-mixture hierarchical model (negative binomial distribution) for Black Creek were then plotted side by side (Figure 2.13).

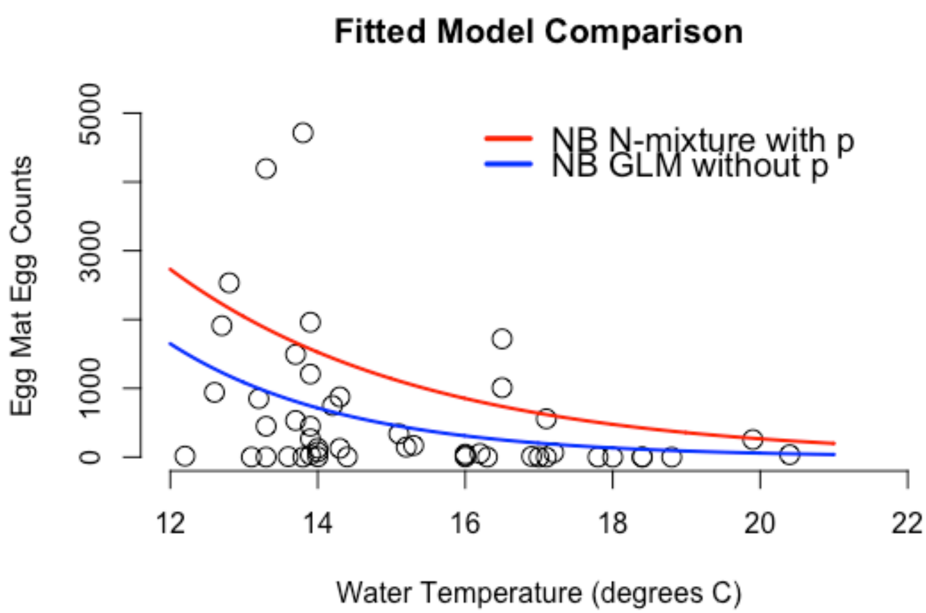

Fig. 2.13. Estimated river herring egg mat egg counts per 58.1cm^2 Black Creek subsample, fit with generalized linear model, and N-mixture model lines against water temperature. The negative binomial (NB) N-mixture model considers probability detection (p) as a function of water velocity. New York, 2017.

The negative binomial N-mixture hierarchical model again predicted higher egg mat egg counts on average when compared to the GLM following negative binomial distribution.

A GLM (negative binomial) with pH, velocity, and moon phase covariates produced the best fitting model at the Fall Kill (Table 2.9).

Table 2.9. Generalized linear model explored at the Fall Kill. The negative binomial distribution resulted in the best fitting model. New York, 2017.

Variable	Estimate	Std. Error	z value	Pr(>|z|)	Sig. Code
(Intercept)	27.521	9.192	2.994	0.003	**
pH	-2.546	1.106	-2.301	0.021	*
Water Velocity	0.416	0.324	1.281	0.200	
Moon Phase	-0.015	0.008	-1.818	0.069	.

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

The null deviance was 50.685 on 30 degrees of freedom while the residual deviance was 38.968 on 27 degrees of freedom. More acidic conditions, increased water velocities and lower light events resulted in increased egg counts. The N-mixture (negative binomial) model estimating egg abundance as a function of pH, and moon phase and detection probability as a function of water velocity, resulted in the best fitting hierarchical model (Table 2.10).

Table 2.10. N-mixture model abundance estimates (log-scale) reported as a function of pH and moon phase, and detection probability estimates (logit-scale) reported as a function of water velocity. The state and observational model are explored simultaneously in this hierarchical model. The negative binomial regression model showed significantly lower AIC index values for The Fall Kill. New York, 2017.

Measure	Variable	Estimate	Std. Error	z value	Pr(>|z|)	Index	Index Value
Abundance	(Intercept)	34.555	13.037	2.650	0.008	AIC	10212.630
	pH	-3.248	1.587	-2.050	0.041		
	Moon Phase	-0.020	0.008	-2.640	0.008		
Detection Probability	(Intercept)	-0.467	0.030	-15.800	<0.001		
	Water Velocity	0.371	0.020	-19.400	<0.001		

Spatial Distribution

ArcGIS was used to map out the coordinates of river herring egg deposition in both Black Creek and the Fall Kill throughout the sampling season. Through the use of remote sensing, the total area of the Fall Kill was estimated to be 836.05m^2. The greatest concentration of eggs per single sampling event, discovered at the Fall Kill was 5,523 eggs, observed on April 20, 2017. This was located in the central strata. Egg concentrations over the entirety of the season were greatest in the upper 2/3rds of the system, and Jenks natural break optimization was applied in ArcGIS to further classify these concentrations (Figure 2.14).

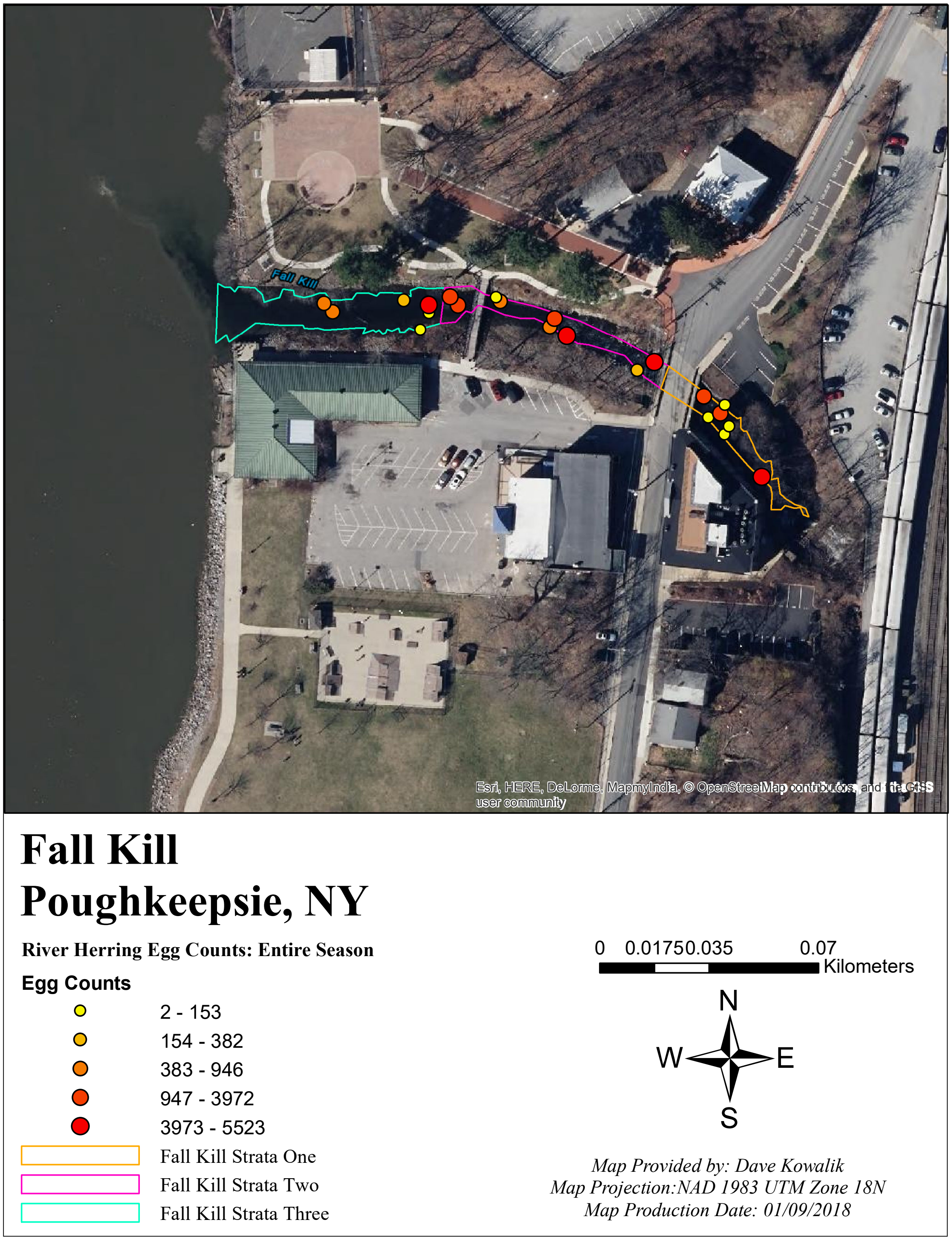

Fig. 2.14. River herring egg concentrations per 58.1cm^2 subsample in the Fall Kill. These counts reflect the entirety of the season. New York, 2017.

The greatest concentration of eggs were found scattered about the upper 2/3rds of the system in both the first half of the spawning run as well as in the second half of the spawning run. Comparatively, the first half of the run experienced greater egg deposition in the lower 1/3rd of the system (Figure 2.15).

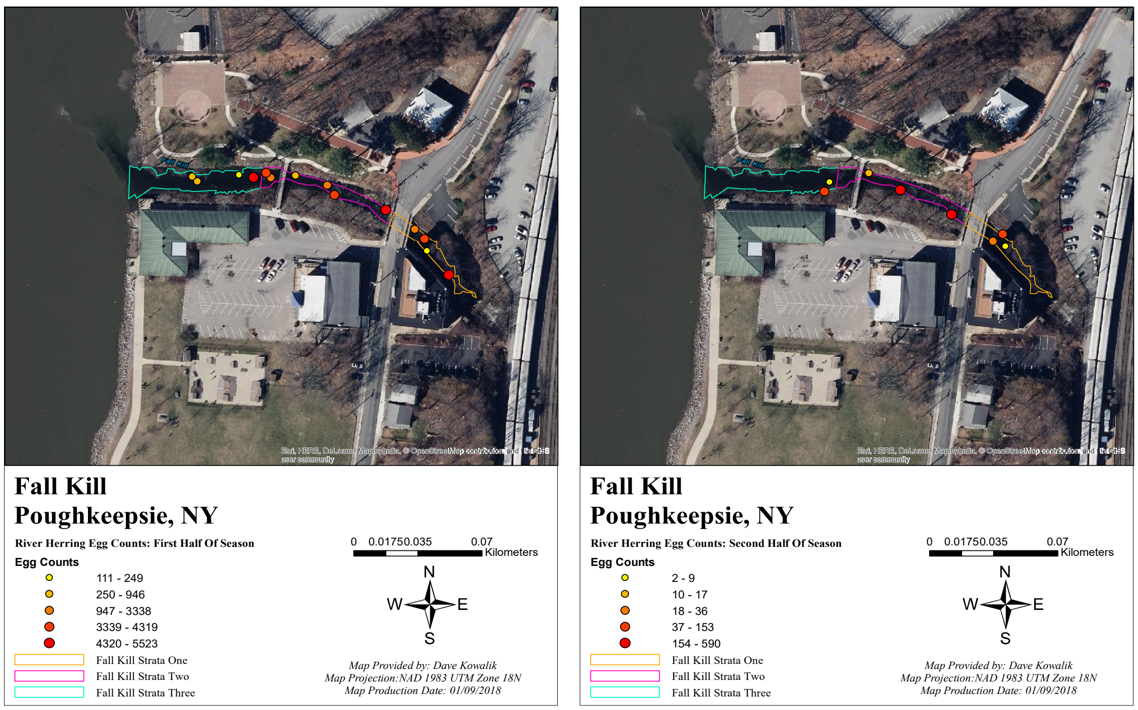

Fig. 2.15. Side-by-side comparison of river herring egg counts recovered in the first half of the spawning run and those recovered in the second half of the spawning run in the Fall Kill. New York, 2017.

The kernel density spatial analysis tool (Beyer, 2004) was applied to the Fall Kill to estimate river herring egg counts based on geographic point data in the tributary. The search radius was defined at $5km^2$ and confined to the extent of the Fall Kill with a 0.25 output cell size. These parameters serve to keep the estimated likelihood tighter in scope (Figure 2.16).

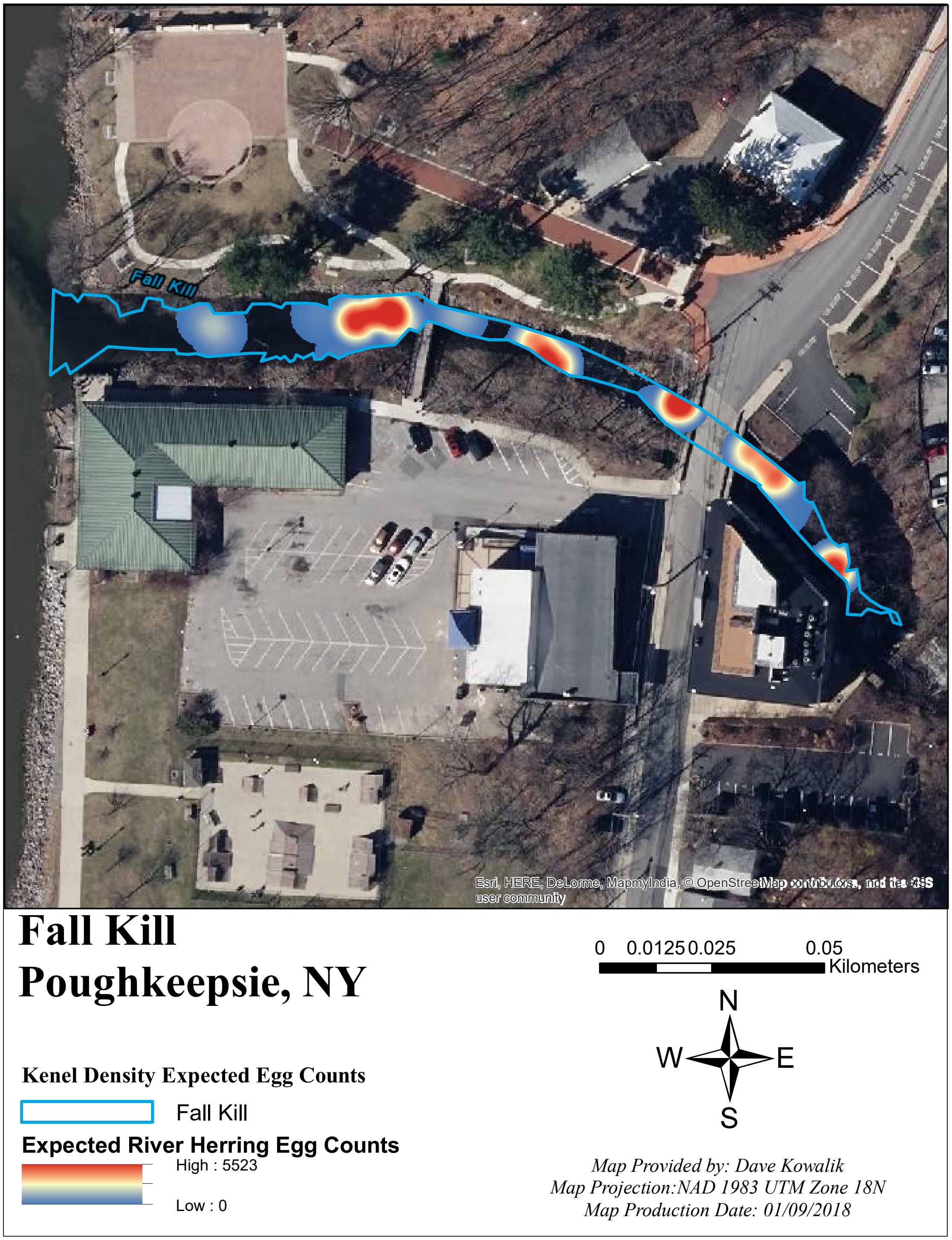

Fig. 2.16. A kernel density map of the Fall Kill showing expected river herring egg counts based on our observed sampling counts. New York, 2017.

The total area of Black Creek was estimated at 46,105.73m^2. Similar to the Fall Kill, Black Creek exhibited the greatest concentration of river herring eggs in the upper 2/3rds of the system over the entirety of the sampling season. The greatest concentration of eggs per single sampling event was 4,714 eggs observed on April 21, 2017, and this was located in the central strata. The egg mat egg concentration, per geographic coordinate is displayed (Figure 2.17).

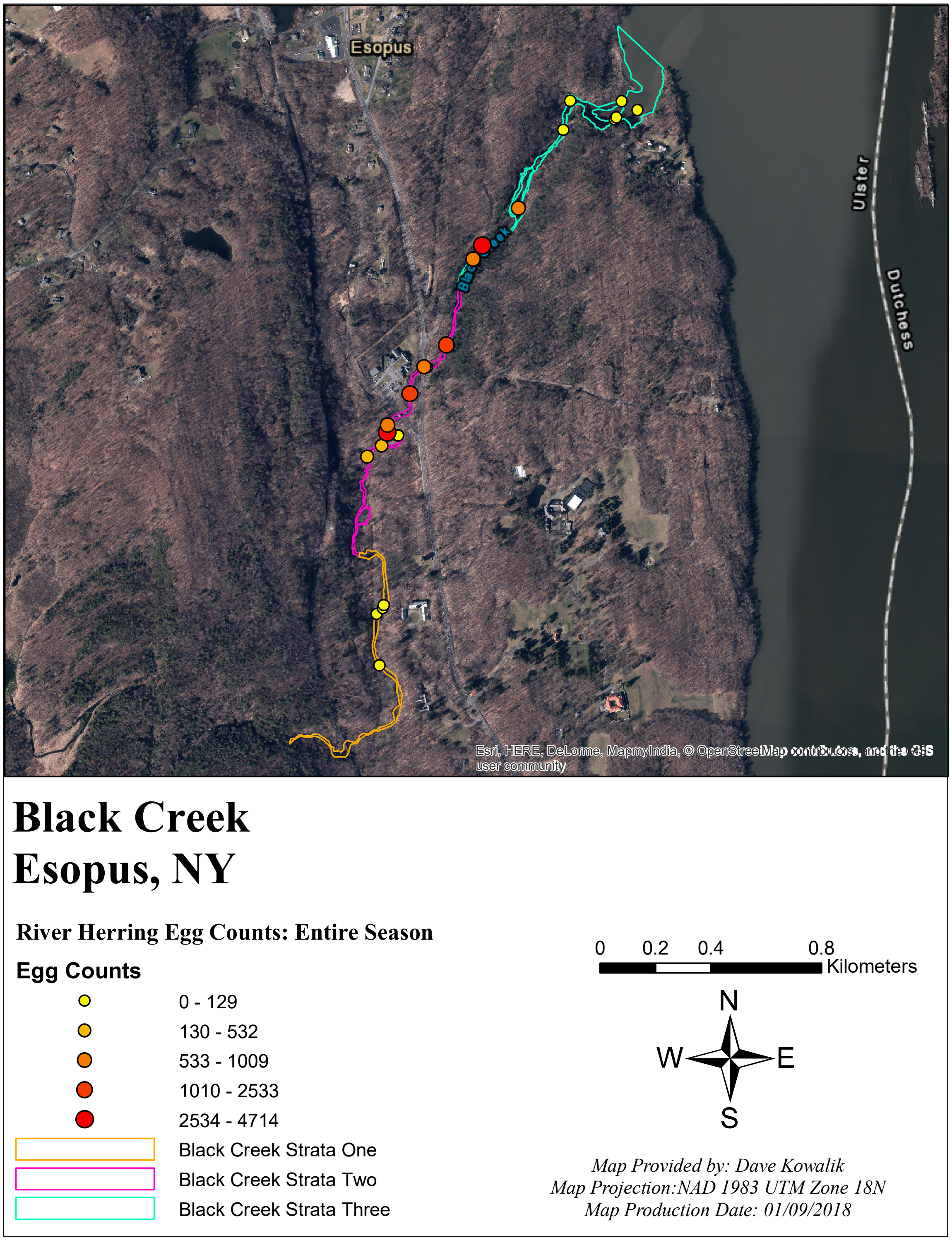

Fig. 2.17. River herring egg concentrations per 58.1cm^2 subsample in Black Creek. These counts reflect the entirety of the season. New York, 2017.

The greatest concentration of eggs were again scattered about the upper 2/3rds of the system in both the first half of the spawning run as well as in the second half of the spawning run. Comparatively, the second half of the run experienced greater egg deposition in the lower 1/3rd of the system (Figure 2.18).

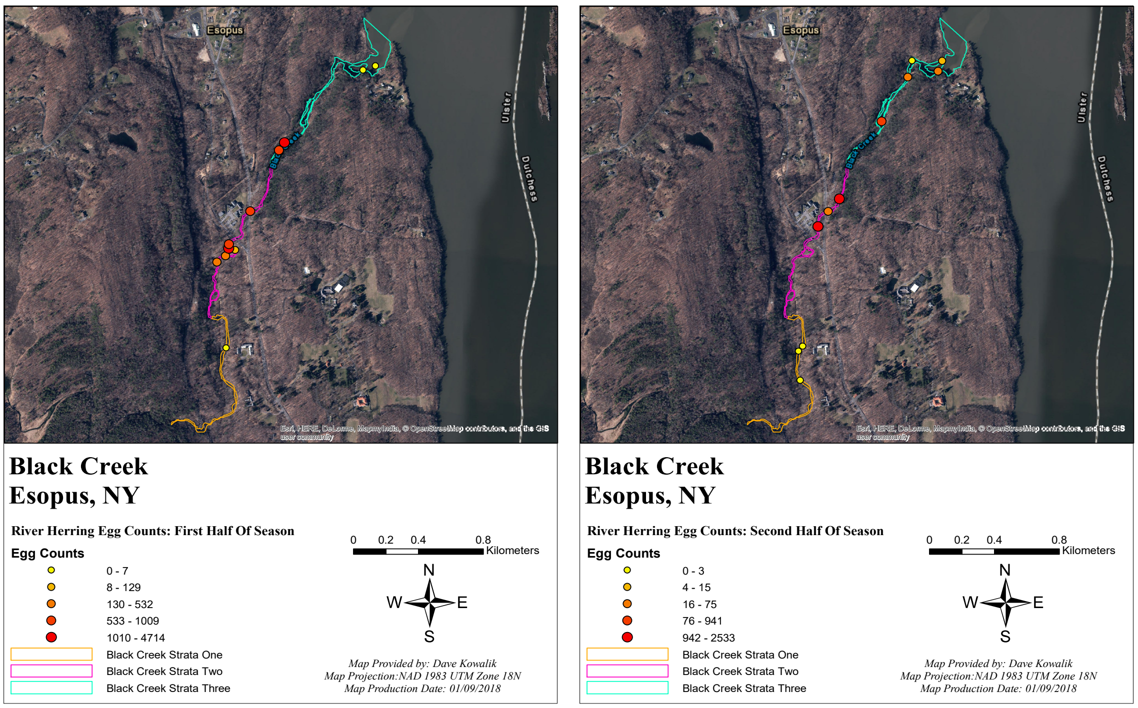

Fig. 2.18. Side-by-side comparison of river herring egg counts recovered in the first half of the spawning run and those recovered in the second half of the spawning run in Black Creek. New York, 2017.

Lastly, the kernel density function (Beyer, 2004) was applied to Black Creek as well to estimate river herring egg counts based on geographic point data in the tributary. The search radius was defined at $5km^2$ and confined to the extent of Black Creek with a 3.99 output cell size. Figure 2.19 shows predicted egg counts, while Figure 2.20 is zoomed in for more practical interpretation.

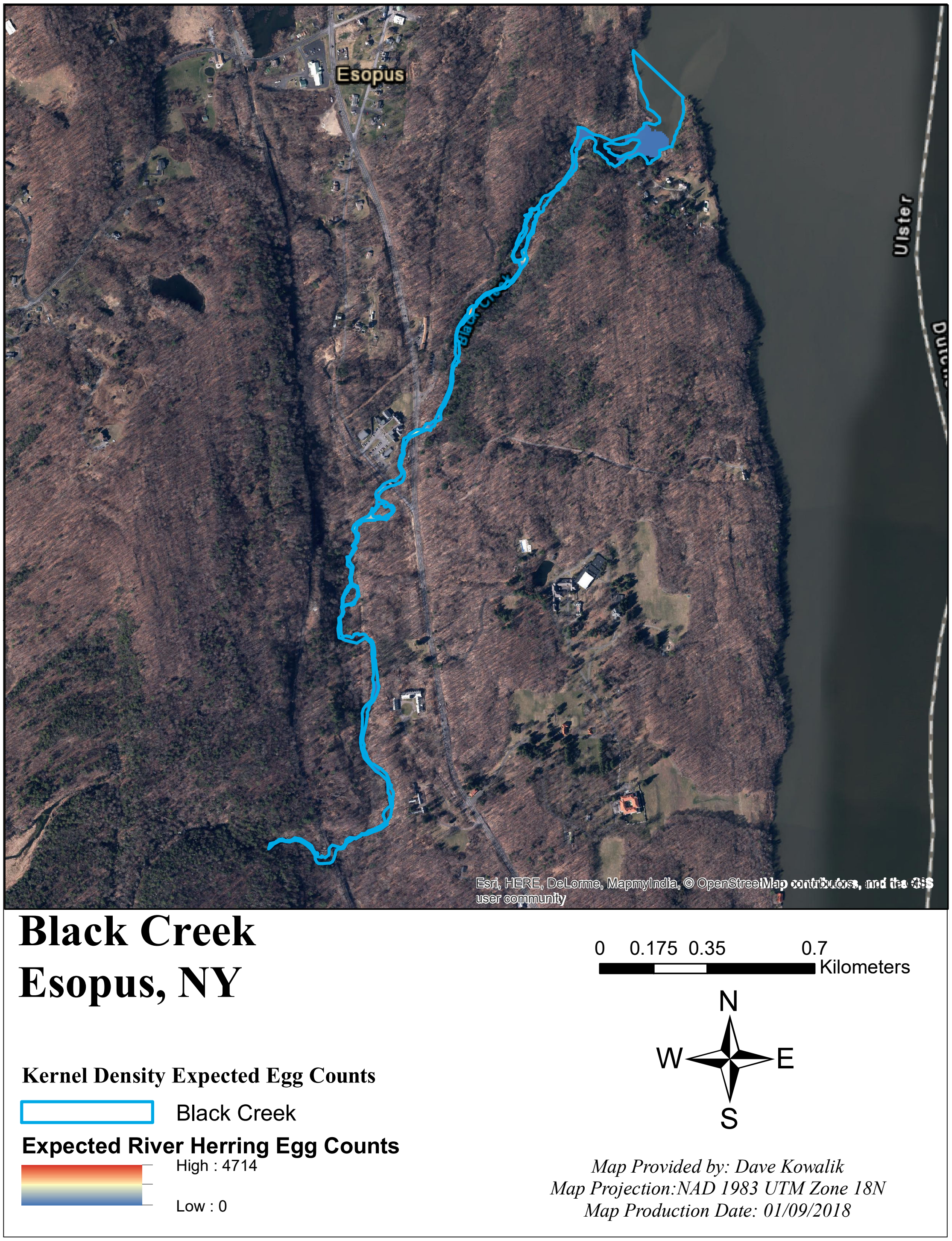

Fig. 2.19. A kernel density map of Black Creek showing expected river herring egg counts based on our observed sampling counts. New York, 2017.

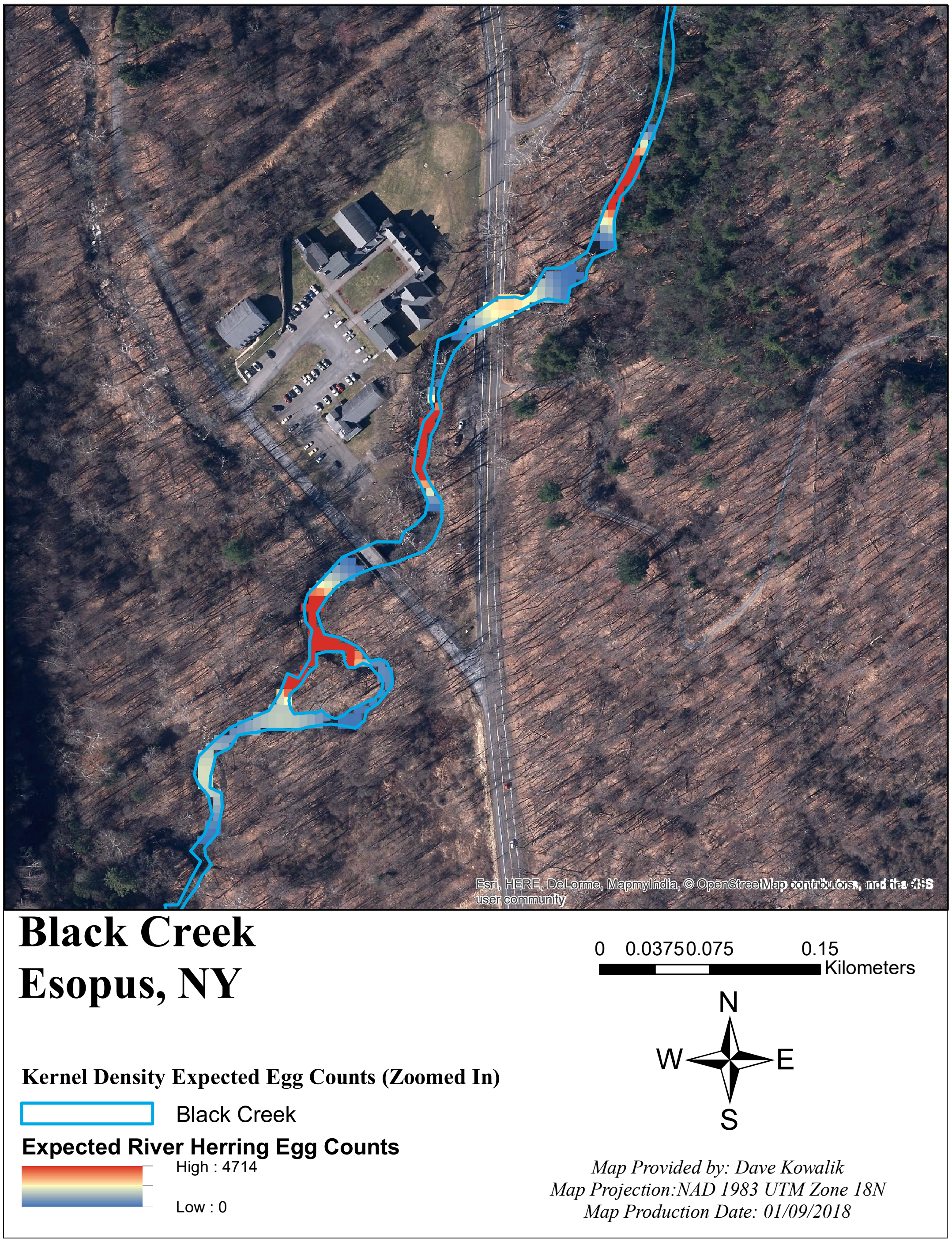

Fig. 2.20. A zoomed in kernel density map of Black Creek showing expected river herring egg counts based on our observed sampling counts. These red hot spots, indicating greater predicted egg counts, are located in the second strata. New York, 2017.

Chapter Two Discussion

The majority of river herring eggs were found in the upper 2/3rds of each respective tributary. Throughout the course of the sampling season, an average of 1,595 eggs per sampling event were recovered in the uppermost two strata from Black Creek, and an average of 2,619 eggs were recovered in the uppermost two strata from the Fall Kill. This compares to an average of 1,303 eggs in the two lower strata of Black Creek, and 2,595 eggs in the two lower strata of the Fall Kill. Egg mats that were moved from their original deployment site, or re-oriented due to angler interference or natural conditions, were omitted from study.

As suggested in previously mentioned literature review, the concentration of river herring eggs and larva deposited over the course of the spawning run followed a multi-modal pattern. A series of decreasing oscillations in Figures 2.7 and 2.8 define pulses of herring egg release and larval spawning. The greatest number of river herring eggs collected was found on April 20, 2017, followed by three more gradually tapering pulses of increased egg deposition. The herring larva follow a similar trend. It is worth noting that due to flooding events in the earliest portions of the potential spawning run, egg mat deployment was limited. Interestingly enough, the duration an egg mat was deployed did not necessitate increased river herring spawning loads. This leads me to believe that spawning takes place in a surge all at once as opposed to a gradual depositing of eggs throughout the course of days.

In terms of river herring egg habitat, the greatest number of river herring eggs found in both tributaries combined were indeed found in lower light events per our hypothesis. The number of river herring eggs found at moon phase percentages below 50% was equal to 53,729, and the number of river eggs found at moon phase percentages greater than 50% was 29,462. In regards to water temperature however, the greatest number of eggs were found between 13-17 degrees C. The number of river herring eggs found at water temperatures between 12-16 degrees C was 838 eggs, and the number of eggs recovered between 13-17 degrees C was 1,051 eggs. Water velocity proved to be the most significant predictor variable in explaining river herring egg abundance over both sites. Contrary to our velocity hypothesis and previous literature review, river herring egg abundance at Black Creek and the Fall Kill appeared to increase significantly until the 2-3m/s threshold. The number of river herring eggs found at water velocities between 0-1m/s was 15,173 eggs, contrasting with 45,746 eggs at 2-3 m/s. In looking at Black Creek exclusively, water temperature appeared to be the important secondary abiotic driver of abundance whereas pH was the complimentary driver for the Fall Kill. With historical incidence of pollution at the Fall Kill, one might further study river herring evolutionary strategies when confronted with fluctuating pH levels due to point source pollution.

As a global model for explaining river herring egg abundance in both tributaries, the N-mixture model following negative binomial distribution performed best. As opposed to the N-mixture models following Poisson and zero-inflated Poisson distributions (respectively), the negative binomial distribution performed better due to overdispersion in the observed data. The N-mixture model, when accounting for a particular covariate's effect on detection probability, appears to suggest greater egg abundance than detection probability naïve GLM's. This effect is highlighted in the global model for both tributaries combined as the GLM could potentially underestimate egg abundance nearing 40cm of depth in figure 2.12. This is not to say that the N-mixture model is not potentially overestimating egg abundance, however, the high detection probability serves to validate these greater egg counts. N-mixture models also appear useful in identifying the overall trend over the course of the time series while accounting for moderate stochasticity.

The *unmarked* (Fisk and Chandler, 2011) package in R was chosen to process hierarchical models over *jagsUI* (Kellner, 2016) due to its faster computational times when accounting for abiotic covariates, reduced error, and also because of its AIC model comparison criteria which could effectively be compared to GLM's utilizing the same indexing. Were this egg mat method of data collection previously implemented in these tributaries, and if previous comparable data sets existed, a Bayesian framework could prove useful in forecasting expected egg abundance. With sound priors established over a greater time series, I believe the Bayesian approach would be useful to implement, especially in considering the examination of multiple tributaries via a large data set.

The side-by-side design of the egg mat housing unit, and orientation in the stream allowed for gear efficacy measurement alongside occupancy modeling. Eggs of other species that were captured appeared to be minimal due to the spatial and temporal variation of spawning organisms during this sampling period. Over the course of the entire season, when accounting for both tributaries combined, 182 of 83,770 total eggs recovered from egg mat subsamples were those belonging to other species. The egg mat collecting surface oriented upstream collected more eggs than the downstream oriented surface on average, when viewing the results of the paired-sample t-test. Seven additional egg mat data collections were excluded from analysis due to re-arrangement within a given tributary. Further securing of egg mats with additional rebar, and trap net anchors during increased flows may prove useful in eliminating issues of mat movement. The presence of river herring eggs was noted at 84% for the upstream collecting surface and at 89% for the downstream collecting surface. Instances where both surfaces detected an absence were eventually factored into the overall detection probability. Future study would benefit from knowing the trajectory, sink rate, and potential roll of the river herring egg to see how far these semi-demersal eggs are traveling in a given section of stream. This would allow for a more precise measure of egg release sites, and would allow for further inspection of egg mat design efficiency.

The mapping of egg mat egg concentrations shows a fairly random deposition of eggs, with the greatest concentrations falling in the central strata of both tributaries. Interestingly, river herring appear to use the entirety of a stream regardless of the timing of the spawning run. This suggests that a given gravid female is just as likely to run the length of the stream to the first impassable barrier in the first half of the season as they are in the second half of the season. This may also be indicative of multi-modal spawning behavior. The interpolation of predicted river herring eggs from central abundance nodes was kept to a minimum, as higher concentrations of eggs were often found near lower concentrations in our actual observations. This served to limit spatial and temporal variation, though some areas that weren't sampled remain open for further interpretation via a systematic sampling approach. Two-way ANOVA was performed to compare strata means, site means, and their potential impact on predicting river herring egg abundance. The strata means were not significantly different from one another, however, the site means differed and Tukey's HSD was conducted to examine the pairwise comparisons (Table 2.11).

Table 2.11. Two-way ANOVA was conducted to compare the means of site and strata as a function of egg abundance. Site level means were found to be significantly different and Tukey's HSD shows the resulting pairwise comparisons. New York, 2017.

Covariate	Levels	Difference	Lower	Upper	P Adjusted
Strata	2-1	485.724	-315.169	1286.617	0.322
	3-1	-220.509	-1021.402	580.384	0.789
	3-2	-706.233	-1525.974	113.507	0.106
Sites	4-3	629.681	80.513	1178.849	0.025

With this being the case, extrapolation of river herring egg abundance to the entirety of the stream based on surface bottom estimation was appropriate. If we extrapolate river herring egg abundance to each tributary at large based on stream bottom surface area, over the course of the entire 50 day sampling season we estimate the population density of river herring eggs to be 61.3 billion eggs, 95% CI [57.4 billion, 65.2 billion]/46,105.73m^2 or 1.3 million eggs/m^2 at Black Creek and 2.26 billion eggs, 95% CI [2.22 billion, 2.30 billion]/836.05m^2 or 2.7 million egg/m^2 at the Fall Kill.

Manipulation of natural or artificial barriers to fish migration, as well as the implementation of supplemental fish passage, should be considered not only based on fiscal merit, but also on the basis of environmental gain. Measuring environmental gain is difficult as extrinsic values are considered, but being able to quantify the intrinsic value serves as a suitable approximation for prioritizing such proposals. The river herring run potential, which was previously undocumented in the Fall Kill, proved to be significant in our study for increasing its habitat enhancement potential. The first impassable barrier of the Fall Kill is indeed natural in origin, but habitat enhancement can also take the form of mitigating anthropogenic inputs throughout the urban setting of the Fall Kill. This study can also be applied to areas where fish passage is being considered, and can be further tailored to a specific species and/or assemblage of species in a given system. The egg abundance data recorded in Black Creek can be paired with adult population, mortality and fecundity estimates to sex the population, forecast successive populations, and provide a broader picture of the spawning dynamics taking place in a tributary.

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Chapter 3

A Comparison of Spawning River Herring Population Methods and Fecundity Estimation in the Tributaries of the Hudson River

Abstract

Spawning river herring population estimates obtained from Smith-Root SR-1601 auto-enumeration technologies were compared against Delta Vision HD underwater camera estimates in Black Creek (New York). The Smith-Root counter is sensitive to detection, however, it is susceptible to the double counting of fish during prolonged observation periods and the equipment itself can be costly and cumbersome. Fisher's F-test showed homogeneity of variance between the two methods of population assessment and the associated two-sample t-test revealed that the means of the Smith-Root based daily population estimates were the same as the Delta Vision camera estimates within a 95% confidence interval. The lower and upper confidence interval bounds were obtained for both methods of population estimation through bootstrapping. The Smith-Root mean, daily population estimate of river herring was 5,750 fish and the Delta Vision camera mean estimate was 5,550 fish. These daily estimation methods were compared against further fecundity and drift net sampling. A mean standing egg crop of 110,094 eggs per mean ovary weight of 32.25g was realized for river herring, 91,722 eggs per mean ovary weight of 26.39g for blueback herring (*Alosa aestivalis*), and 121,021 eggs per mean ovary weight of 35.59g per alewife (*Alosa pseudoharengus*). Only alewife were noted in Black Creek and the Fall Kill (New York). With sampling efforts revealing a 50:50 ratio of female alewife to male alewife in Black Creek, we multiplied the mean standing egg crop of 121,021 alewife eggs by

2,775 females (mean daily estimate) to obtain a mean daily egg input of 335.8 million eggs, 95% CI [237.2 million, 454.4 million] into Black Creek. The mean number of alewife eggs being input into the Fall Kill per day was 516.6 million eggs, 95% CI [202.3 million, 830.8 million]. Drift net egg counts were extrapolated to the entire volumes of Black Creek and the Fall Kill to obtain egg population estimates. The total number of eggs estimated from April 17, 2017 to June 5, 2017 for the entire volume of Black Creek was 10.2 million eggs. The total number of eggs estimated over the same sampling period for the entire volume of the Fall Kill was 15.2 million eggs. This drift net egg productivity proved comparable to previous research estimates, however, the fecundity and visual count based egg productivity estimates in our study allude to a significantly greater estimation of egg inputs.

Introduction

Smith-Root SR-1601 potentiometric fish counters use water conductivity changes to detect and enumerate macro-organisms (SR-1601 Fish Counter, 2018). With 16 detection tunnels, this technology is effective for simultaneous measurements of ubiquitous organism such as spawning river herring. A Smith-Root SR-1601 has been used in Black Creek (Esopus, New York) since 2013 to acquire daily population estimates of spawning river herring (essentially alewife). While highly accurate (approximately 98% count data accuracy), this technology is expensive and requires regular maintenance to ensure debris does not obstruct counting efforts. Double counting exists, and an estimation of sex ratio is not immediately available as well. We explore the implementation of visual counts in conjunction with drift nets, post-mortem ovary analysis, and Smith-Root counts as a means for offsetting the unfavorable effects associated with the SR-1601.

VisuCount run size estimation software was developed by Gary Nelson for river herring population surveys and has been used by community watershed organizations and government entities throughout the Northeast since 2010 (Nelson, 2006). An accompanying guide for statistical sampling design was implemented in 2006, and the VisuCount software was developed in 2010 to deal with ineffective data collection and analysis (Nelson, 2006). Surveys have previously relied upon in-person visual counts at fish ladders (one example) to record counts, however, this requires frequent on site visits, may make lowlight conditions difficult for counting, and is typically relegated to sites of supplemental fish passage (Nelson, 2006). Delta Vision HD and SeaViewer 950-Sea Drop Analog under water cameras, and single channel dvr recorders offer a potential means for overcoming the aforementioned obstacles associated with the surveying of fish, as well as a reduction in error.

Underwater cameras and dvr recorders can be used to capture fish passage at any moment of a sampling day, and the implementation of relatively brief stratified sampling blocks allows for a possible reduction in the double counting of fish. Cameras can also be used in conjunction with a fish weir to effectively funnel fish into an effective field of view. This also allows for greater flexibility in sites selected for enumeration, and does not require in-person observation at sites of supplemental fish passage. These video counts will ultimately be compared with Smith-Root counts.

The issue of sexing river herring still persists for visual run size estimation, however, knowing the average number of eggs carried by a given gravid female river herring (alewife in particular) and the estimated number of eggs per volume of a tributary, will allow for estimation. Fecundity studies have been conducted on river herring in the tributaries of the Hudson River in order to establish standing egg crop estimates (Limburg and Blackburn, 2003). Similarly, drift net studies have put forth estimates of alewife egg production per volume of a tributary (Lake and Schmidt, 1998). Previous unpublished data collected by the DEC, from 2013 to the current year, estimate the ratio of female to male alewife to be roughly 50:50 in Black Creek. Through the cross referencing (and validation where applicable) of Smith-Root counts, visual counts, fecundity analysis, and drift net analysis we estimate gender demography and the greater population dynamics picture of spawning river herring.

Hypothesis

In regard to our study, spawning behavior is defined as milling and migration within a given tributary between the months of April and June of 2017 (Sethi and Tanner, 2014). We hypothesize that the mean daily population estimate of spawning river herring estimated from the Smith-Root counter will be the same as the mean population estimate acquired from video counts on the days that measurement are shared between the two forms of enumeration.

Methods

Fecundity

Gravid female river herring were collected from the main stem of the Hudson River from April 20, 2017 to May 23, 2017 for post-mortem dissection and ovary extraction. A 91m long haul seine composed of 5.1cm stretch mesh, with catch chamber, was deployed to procure these fish. Total fish length (mm), fish wet weight (to nearest 0.01g), scale sample, otolith, sex, species, sample site and river mile were recorded. Select gravid females were placed on ice and the ovaries were extracted and weighed (to nearest 0.01g), labeled and preserved in a whirl-pak freezer bag with 95% EtOH, and refrigerated (Lake and Schmidt, 1998). The sexual condition of the female was also documented and those fish categorized as spent, due to the presence of blood with outstanding eggs, were documented but excluded from subsequent regression analysis (Normandeau, 2007).

Three subsamples from each fish ovary were weighed (nearest 0.01g) and counted (Lake and Schmidt, 1998; Limburg and Blackburn 2003). The subsamples weighed a minimum of 0.5g and were taken from the anterior, middle, and posterior portions of the left ovarian lobe (Limburg and Blackburn 2003). The mean number of eggs calculated per each of the three ovary subsamples was then extrapolated to the total number of eggs per weight of the entire gonad.

The ovary subsamples were placed in separate dram vials with water and mild soap, agitated, and stored for a week. After a week, these subsampled ova were placed in a petri dish and teased apart from the deteriorated ovarian tissue through manual manipulation with forceps. This petri dish was covered with a black lid, and scanned with an Epson Perfection V19 flatbed scanner at 800dpi resolution (Klibansky and Juanes, 2008). It was important to ensure that the river herring ova were in a single layer, and separated well from any residual ovarian tissue before scanning. ImageJ software was used for the auto-enumeration of the river herring eggs obtained from post-mortem ovary extraction, and the black lid provided further contrast (Klibansky and Juanes, 2008).

Regression analysis was performed to illustrate the relationship between fecundity and total fish length (Lake and Schmidt, 1998). Fecundity and fish age, as well as fish wet weight and total ovary weight, were also examined. The mean number of river herring eggs produced per gravid female was then standardized to the allometric feature exhibiting the greatest statistical significance. This allowed for potential sexing of spawning river herring, as well as potential egg input into a given tributary when compared to video counts, Smith-Root counts and drift net counts.

A gonadosomatic index and Fulton condition factors were noted for each fish (Limburg and Blackburn, 2003). According to Limburg and Blackburn (2003), the gonadosomatic index is defined as the ratio of gonad weight to somatic weight (total fish wet weight less the ovaries). From this index, Fulton condition factors were derived as

$$\text{Contition} = W_{somatic}/(TL^5)$$

where $W_{somatic}$ is the somatic weight for a given female fish, and TL is the total length of a given female fish (Limburg and Blackburn, 2003).

Drift Net Deployment

Drift nets were deployed in Black Creek and the Fall Kill alongside egg mats at the same time the egg mats were being set. The sampling season took place again from April 17, 2017 to

June 5, 2017. Drift nets were placed for 300s (5 minute) durations and abiotic conditions were recorded with a YSI multi-parameter sonde. River herring egg abundance measurements, abiotic stream conditions, and spatial distribution were recorded for drift net sampling events under the same protocol as egg mat sampling.

A daily population estimate of river herring eggs (per entire volume of a tributary) being exported from a given tributary was extrapolated from drift net sampling events. The number of eggs calculated per volume of drift net for a given duration was extrapolated to the number of eggs per stream discharge over the course of a day (Lake and Schmidt, 1998).

The daily population estimates of river herring eggs obtained from drift net samples were divided by the mean number of egg per standardized female river herring (fecundity analysis) in order to obtain daily population estimates of spawning female river herring. These daily population estimates of spawning female river herring could be analyzed in conjunction with our visual counts, Smith-Root counts, and assumed Hudson River tributary gender ratios (river herring) derived from sampling observations.

Visual Counts

A SeaViewer 950-Sea Drop Analog Camera and single channel dvr recorder were installed approximately 0.05km upstream of the Fall Kill and Hudson River interface. Similarly, a Delta Vision HD underwater camera, and single channel dvr recorder were placed 0.5km upstream of the Black Creek and Hudson River interface at the site of the Smith-Root SR-1601 multi-channel fish counter. Cameras were checked daily for proper functioning and to ensure visibility. To aid in the visible detection of river herring, a sheet of 3M reflective material was placed in the field of view to provide greater contrast against passing fish. A rigid panel weir was also placed at the site of each camera to effectively funnel fish into the field of view.

Camera footage and subsequent fish counts were documented daily from April 15, 2017 to May 20, 2017. Potential filming days characterized by above average flows, and conditions unsuitable for weir operation, were omitted due to poor visibility and potentially hazardous ecological impacts. Fish were counted in intervals based on one-way stratified random sampling (St1WRS) techniques (Nelson, 2006). With St1WRS, each day of the run served as the stratum and six random, 20-minute intervals were observed (Nelson, 2006). The free statistical software program VisuCount was used to process this count data alongside relevant abiotic factors (Nelson, 2006). The mean number of herring counted per a particular unit of time for each day (*k*) is modeled by

$$\hat{\bar{y}}_k = \frac{\sum_{i=1}^{n_k} y_{k,i}}{n_k}$$

where $\hat{\bar{y}}_k$ is the mean count on day *k*, y_k is the *i*th count on day *k*, and n_k is the daily number of time units sampled during the sampling season (Nelson, 2006). The total run size ($\hat{Y}$) under St1WRS would then be estimated theoretically as

$$\hat{Y}_{St1WRS} = \sum_{k=1}^{L} N_k \times \hat{\bar{y}}_k$$

where N_k is the total number of time units during during day *k*, and *L* is the number of days of the run (Nelson, 2006).

The daily spawning river herring population estimates obtained from video counts were compared with the corresponding daily fish estimates provided by the Smith-Root counter located at Black Creek, and also the estimated fish counts derived from drift net egg and fecundity extrapolation. This will serve the multifold purpose of comparing daily population estimates between three different enumeration methods, extrapolation of daily fish estimates to the Fall Kill (which does not have a Smith-Root fish counter in place), and limitation of double counting and bycatch. It may reduce the need for cumbersome and costly counter technologies.

Smith-Root Counts

A Smith-Root SR-1601 multi-channel fish counter was placed 0.5km upstream of the Black Creek and Hudson River confluence and measurements were taken from April 11, 2017 to May 20, 2017. This counter uses a system of tunnels in which fish pass through and can be counted simultaneously via a potentiometric bridge (SR-1601 Fish Counter, 2018). In regard to our study, a rigid panel weir was installed at the site of this counter, and fish were funneled through eight tunnels where they were counted simultaneously.

A daily adult river herring population estimate for Black Creek was obtained, and ultimately compared against daily adult river herring population estimates obtained from the Delta Vision HD underwater camera in Black Creek. Similar to the weir management scenarios in the Fall Kill, the weir was implemented and/or removed in accordance with turbulent water events. Those measurement days characterized by overlap between the Smith-Root counts and the Delta Vision HD underwater camera counts in Black Creek were compared. The daily population estimates were compared using the *rcompanion* (Mangiafico, 2017) package in R and 95% confidence intervals were estimated through bootstrapping.

Results

Fecundity

157 gravid river herring females were collected from Haverstraw Bay (RM 37) to Albany (RM 139)(Figure 3.1).

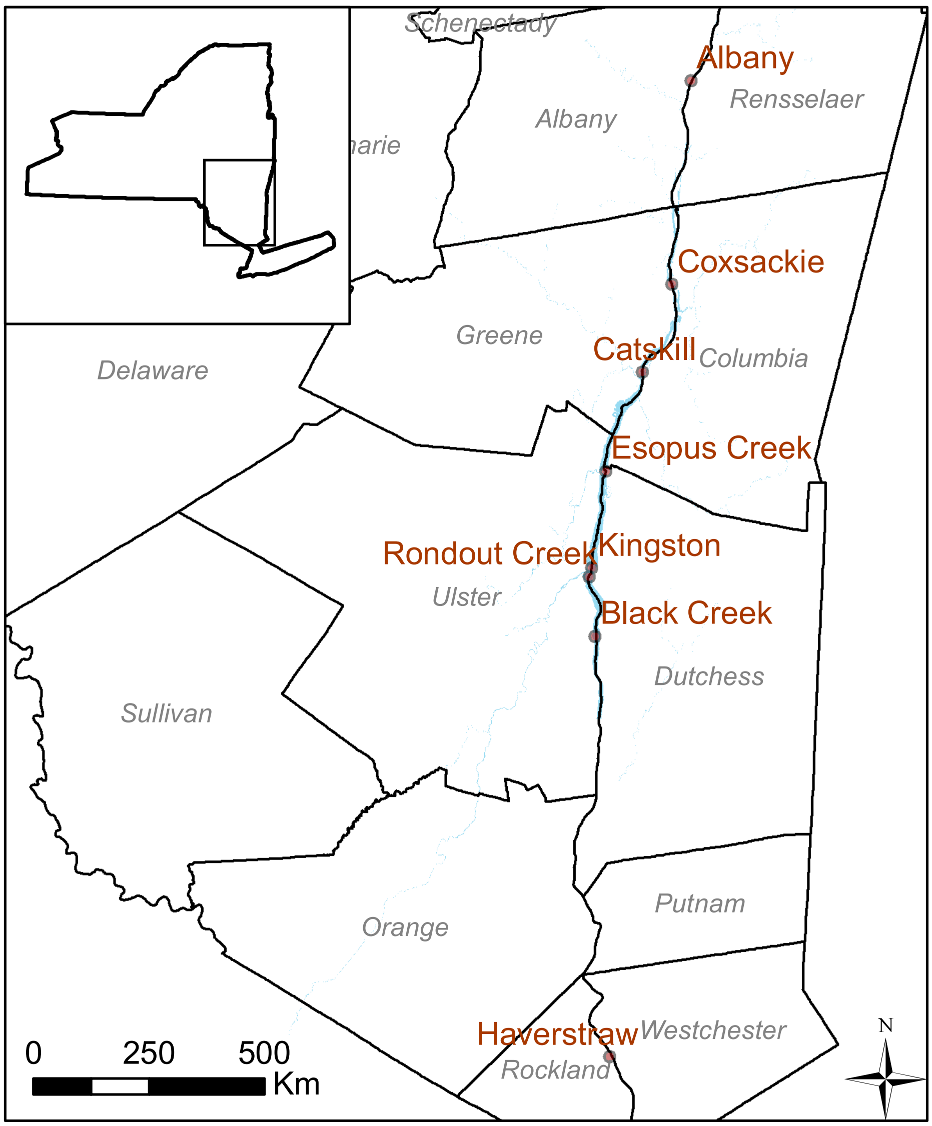

Fig. 3.1. River herring haul seine sites. Gravid females were collected from Albany to Haverstraw for fecundity analysis. New York, 2017.

Of those 157 females, 46 were blueback herring and 111 were alewife. Twenty-eight females were classified as spent and they all happened to be alewife. Fish collected at Black Creek were excluded from analysis as they were spent, and fish collected in Haverstraw were excluded as gill nets were used. The relationship between river mile and total eggs per river herring ovary proved insignificant (Table 3.1).

Table 3.1. The mean number of alewife, and blueback herring eggs per gravid female are recorded per sampling site. Sites where blueback herring were not collected are denoted by zero. New York, 2017.

Sample Site	River Mile	Alewife Eggs	Blueback Herring Eggs
Albany	139	120264	95246
Coxsackie	125	111631	86058
Catskill	115	112771	99105
Esopus Creek	101	117684	100145
Kingston	96	84692	0
Rondout Creek	91	93806	91692

A visual summary of the total number of eggs collected per river herring ovary over the course of the sampling season is shown (Figure 3.2).

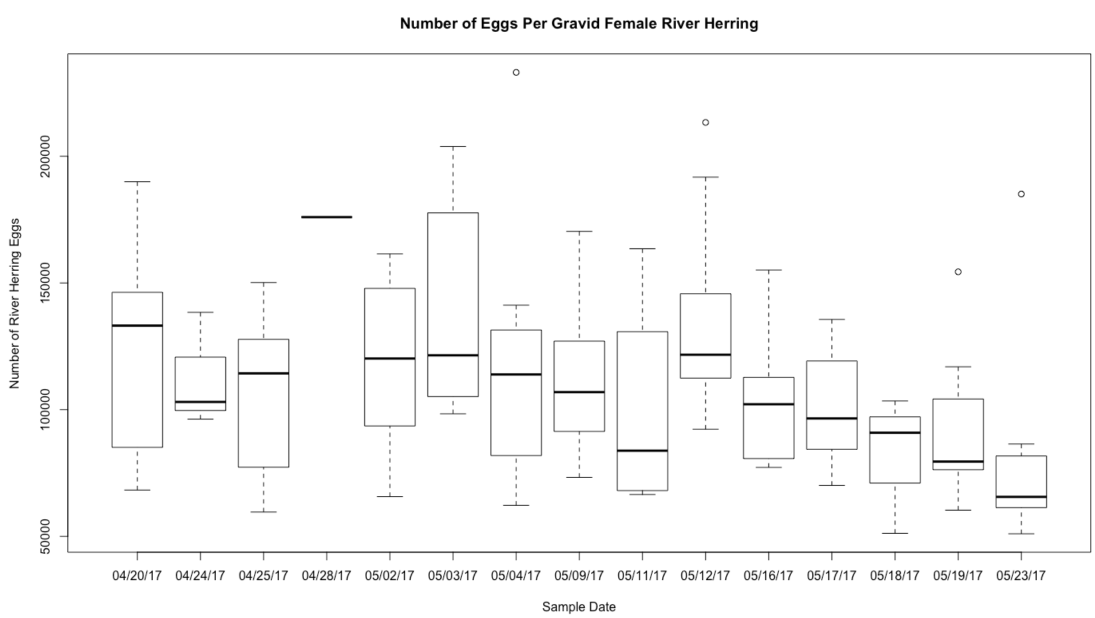

Fig. 3.2. The number of river herring eggs collected per ovary throughout the course of the sampling season. Fish categorized as spent are excluded. New York, 2017

A scanned image of river herring eggs separated from the ovarian tissue is depicted (Figure 3.3).

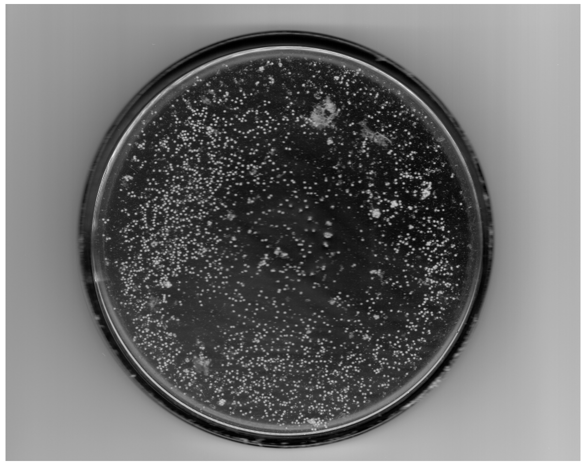

Fig. 3.3. Scanned image of river herring ova separated from the ovarian tissue. The petri dish housing these ova was covered in a lid painted black to provide greater contrast for subsequent image analysis. New York, 2017.

Total ovary weight, total fish wet weight, total fish length, and fish age proved significant (all with $p < 0.001$) in predicting standing egg crop per individual river herring under linear regression (Figure 3.4).

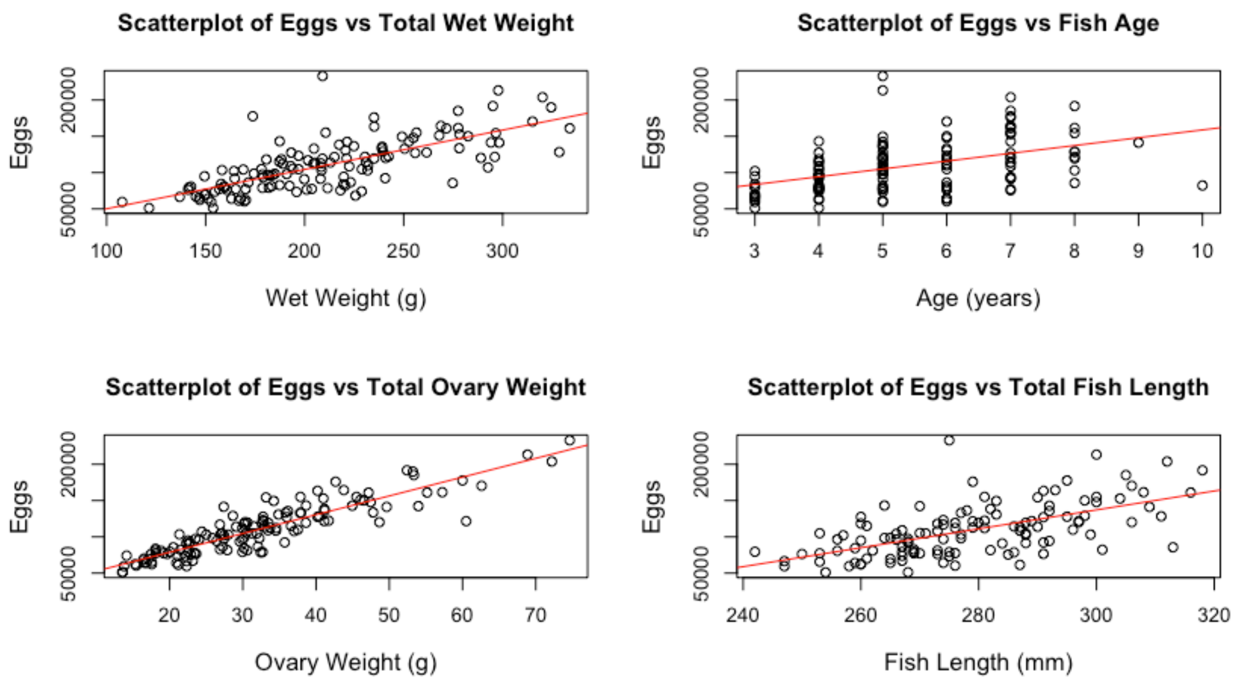

Fig. 3.4. Scatterplots of total eggs per river herring ovary against significant explanatory variables. Simple linear regression was conducted. New York, 2017.

The same scenario was also apparent when modeling blueback herring individually (Figure 3.5) as well as alewife individually (Figure 3.6).

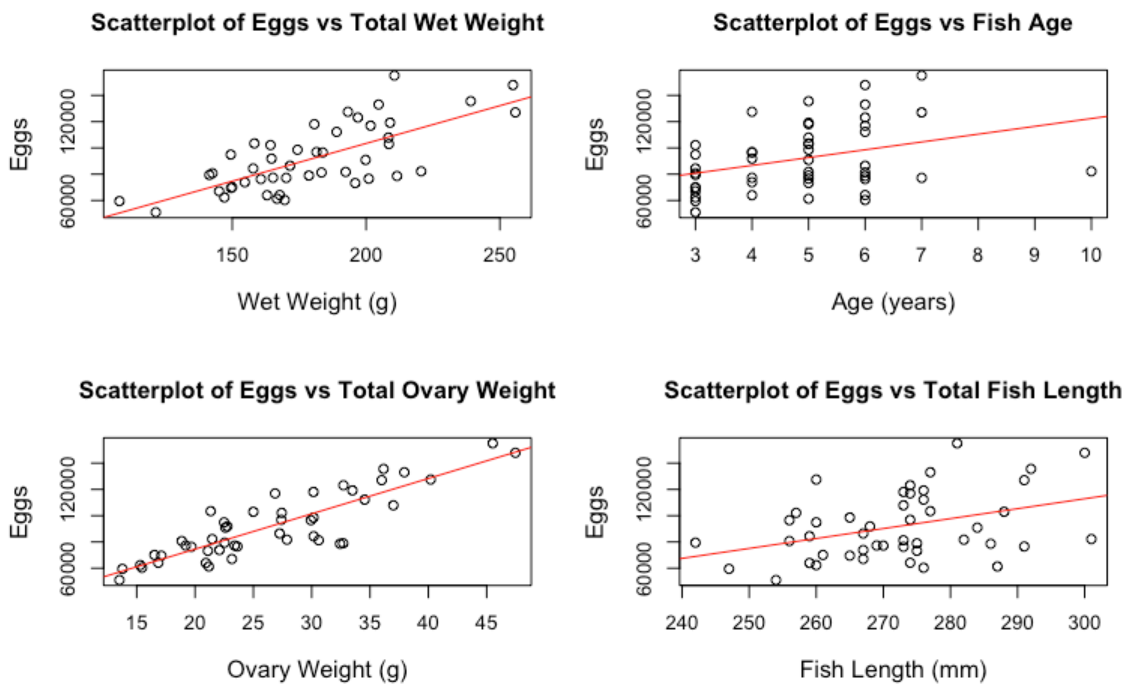

Fig. 3.5. Scatterplots of total eggs per blueback herring ovary against significant explanatory variables. Simple linear regression was conducted. New York, 2017.

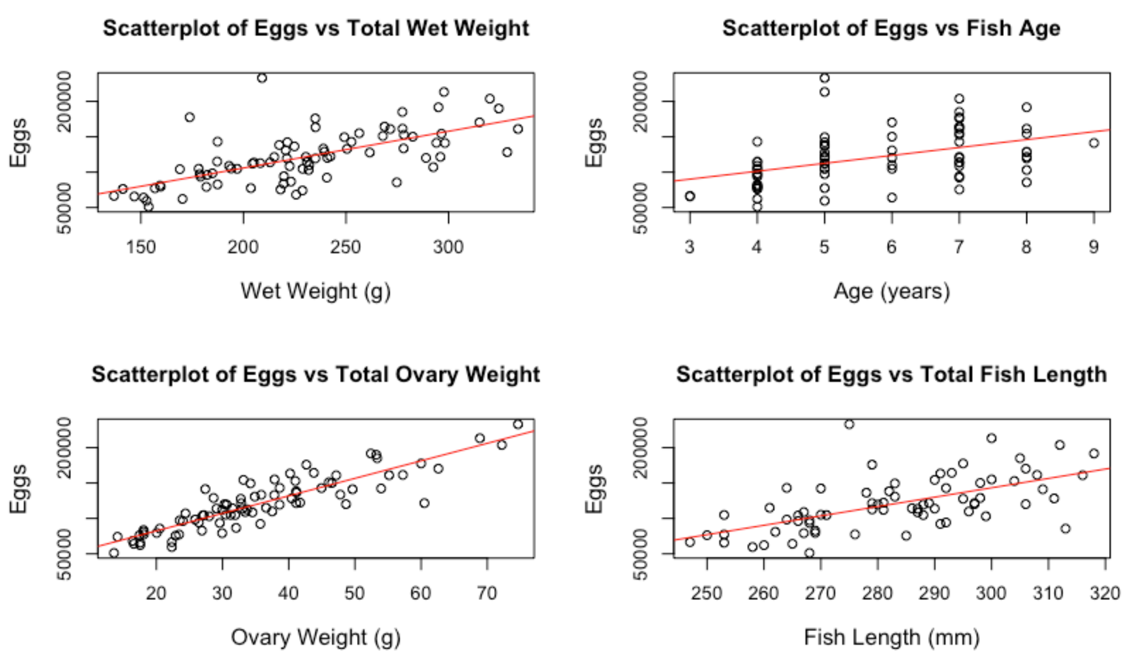

Fig. 3.6. Scatterplots of total eggs per alewife ovary against significant explanatory variables. Simple linear regression was conducted. New York, 2017.

A mean standing egg crop of 110,094 eggs per mean ovary weight of 32.25g was realized for river herring, 91,722 eggs per mean ovary weight of 26.39g for blueback herring, and 121,021 eggs per mean ovary weight of 35.59g per alewife. Total ovary weight was the most significant explanatory variable for predicting the standing crop of eggs regardless of species (Table 3.2).

Table 3.2. Simple linear regression was conducted to find the predictor variable most suitable for standardizing mean river herring, blueback herring and alewife eggs per ovary. Total ovary weight was most significant in predicting eggs per ovary. New York, 2017.

Species	Variable	Estimate	Std. Error	t value	Pr(>|t|)	Sig. Code
River Herring	(Intercept)	26920.1	3894.7	6.912	<0.001	***
	Total Ovary Weight	2578.9	112.4	22.941	<0.001	***
Blueback Herring	(Intercept)	20757.6	6417.0	3.235	0.002	**
	Total Ovary Weight	2689.1	232.6	11.562	<0.001	***
Alewife	(Intercept)	32904.3	5458.4	6.028	<0.001	***
	Total Ovary Weight	2475.6	143.3	17.281	<0.001	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

The residual standard error was 16,160 on 127 degrees of freedom, the multiple R^2 was 0.805, the adjusted R^2 was 0.8041, and the AIC was 2,870.853 when looking at both species combined.

Alewife were the only species observed in Black Creek and The Fall Kill, therefore in addition to standardizing river herring standing egg crop to total ovary weight, we also standardized alewife standing egg crop to total fish length, total wet weight, and age as well. A mean value of 106,228 eggs was realized for alewife measuring an average total length of 272mm. 121,021 eggs were realized for alewife weighing an average of 229.08g. 110,733 eggs were realized for alewife averaging 4.84 years of age.

A total of 28 of the 111 female alewife captured were categorized as spent, and of the remaining 83 considered for analysis, the total ovary weights of female alewife captured ranged from 13.60g-74.64g. The total length of female alewife captured ranged from 247mm-318mm.

The total wet weight of female alewife captured ranged from 136.90g–333.84g. The age of female alewife captured ranged from three years to nine years. The number of times a blueback herring and/or alewife had spawned previously in their existence showed a significantly positive association ($p < 0.01$, and $p < 0.001$ respectively) with an increase in eggs amassed within a given fish ovary (Figure 3.7).

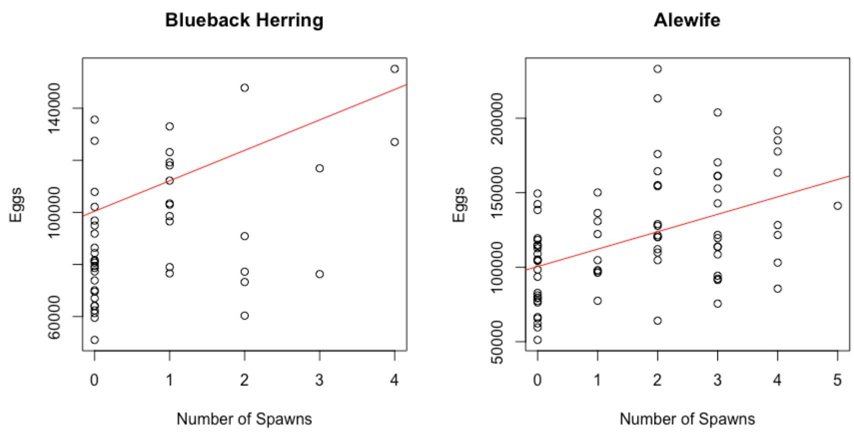

Fig. 3.7. Scatterplots of total eggs per river herring ovary against the number of spawns. Alewife and blueback herring are compared through simple linear regression. New York, 2017.

Julian date, age, total length, river mile and number of spawns were insignificant in predicting river herring gonadosomatic index. River herring Fulton condition factors were significantly associated with river mile in a negative direction ($p = 0.001$). Julian date showed no significant relationship with river herring Fulton condition factors. In looking at blueback herring specifically, gonadosomatic index was insignificant and the Fulton condition factors were significantly associated with river mile ($p < 0.001$). Both the gonadosomatic index and Fulton condition factors for Alewife were insignificant when compared to the same covariates.

Drift Net Deployment

In differing from the egg mat portion of this research, drift nets were deployed to generate a daily estimate of drifting river herring eggs per the entire stream volume of both Black Creek and the Fall Kill. The number of river herring eggs captured during drift netting events showed a general decline on the whole over the course of the sampling season from April 17, 2017 to June 5, 2017 (Figure 3.8).

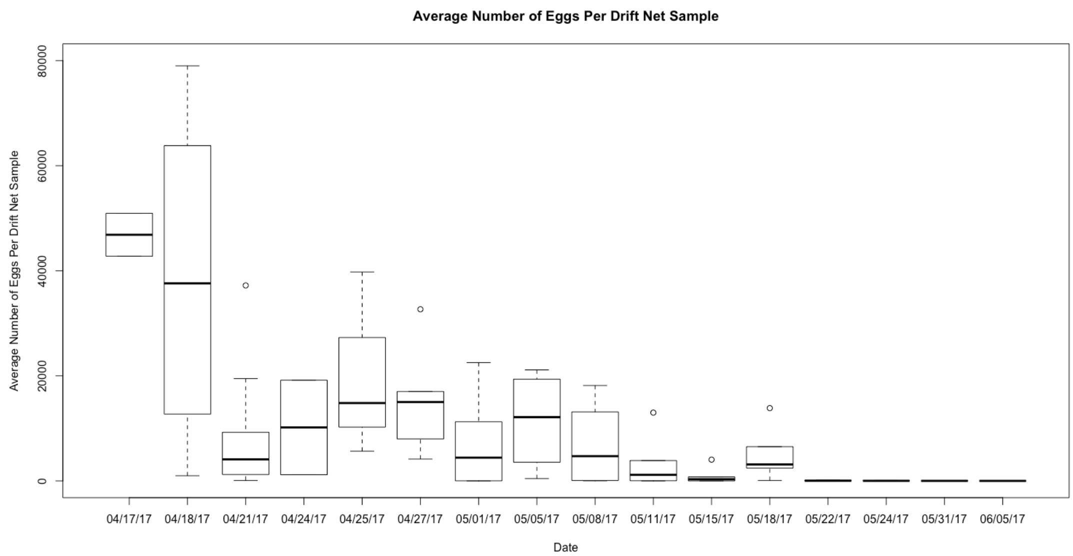

Fig. 3.8. Box and whisker plot of river herring eggs collected from Black Creek and Fall Kill drift net subsamples combined. New York, 2017.

River herring larva collected from drift net samples showed a similar decreasing pattern over the course of the season (Figure 3.9).

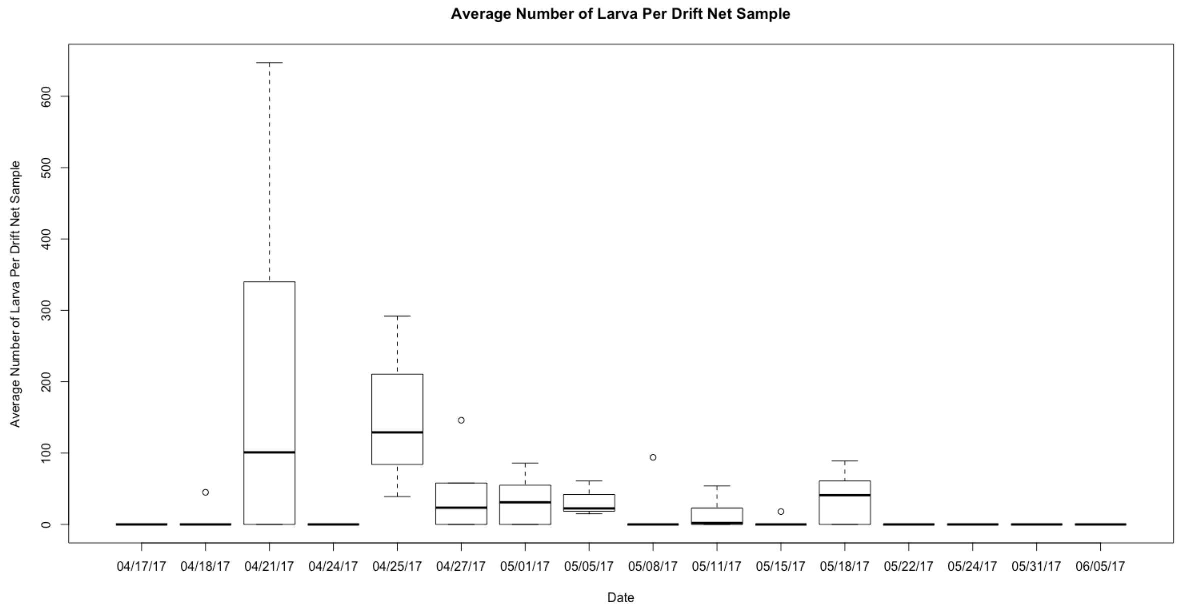

Fig. 3.9. Box and whisker plot of river herring larva collected from Black Creek and Fall Kill drift net subsamples combined. New York, 2017.

The daily population estimate of river herring (essentially alewife) eggs for both the Fall Kill and Black Creek were extrapolated from drift net egg counts to the entirety of a tributary's total volume. The total number of eggs estimated from April 17, 2017 to June 5, 2017 for the entire volume of Black Creek was 10.2 million eggs. The total number of eggs estimated over the same sampling period for the entire volume of the Fall Kill was 15.2 million eggs.

Visual Counts

Alewife were the only species of river herring found participating in spawning behavior in both Black Creek and The Fall Kill. The daily population estimates of spawning alewife obtained from video counts in Black Creek were recorded from April 18, 2017 to May 20, 2017, with some days omitted due to previously described viewing conditions (Table 3.3).

Table 3.3. Daily population estimate of spawning alewife in Black Creek. New York, 2017.

Day	Total Fish	SE	df
4/18/17	9315	2297.487	4
4/19/17	1113	488.647	7
4/20/17	4157	1733.591	7
4/21/17	14766	10567.434	5
4/24/17	12075	5810.922	3
4/26/17	5589	2243.083	3
4/27/17	8970	4692.296	6
4/28/17	3876	1604.95	5
4/29/17	9488	4817.668	7
4/30/17	13672	7454.794	6
5/1/17	3841	1458.337	5
5/2/17	2326	805.59	6
5/3/17	4054	2095.113	7
5/4/17	4564	1928.601	6
5/5/17	5646	3347.076	5
5/10/17	7395	1932.406	5
5/11/17	6167	4293.805	7
5/12/17	7331	3857.438	7
5/13/17	569	199.744	3
5/17/17	1918	461.071	4
5/18/17	503	212.524	6
5/19/17	242	140.329	7
5/20/17	86	50.228	3

April 21, 24, and 30 of the 2017 sampling season, were characterized by large pulses of estimated alewife eclipsing the 10,000 fish mark. An average of 5,550 alewife were estimated per day in Black Creek over the course of these provided dates.

The daily population estimates of spawning alewife obtained from video counts in the Fall Kill were recorded from April 15, 2017 to May 19, 2017, with some days again omitted due to previously described viewing conditions (Table 3.4).

Table 3.4. Daily population estimate of spawning alewife in The Fall Kill. New York, 2017.

Day	Total Fish	SE	df
4/15/17	7694	4193.752	3
4/16/17	4163	3371.673	5
4/17/17	17397	5957.265	7
4/18/17	21537	4386.086	7
4/19/17	7393	2513.174	6
4/20/17	6607	2832.261	3
4/23/17	13558	4110.673	7
4/24/17	5624	1791.686	3
4/27/17	27324	13150.925	3
4/28/17	11954	2571.147	7
4/29/17	18199	3432.252	7
4/30/17	8720	1405.797	7
5/1/17	5994	2293.002	7
5/2/17	4223	1347.276	4
5/3/17	8625	2839.806	4
5/4/17	4678	834.878	4
5/5/17	2932	1801.805	1
5/10/17	3295	1259.85	3
5/11/17	705	173.837	8
5/12/17	172	111.057	3
5/18/17	172	169.982	1
5/19/17	104	101.989	1

An average of 8,230 alewife were estimated per day in the Fall Kill over the course of these aforementioned dates. The daily alewife population estimates in the Fall Kill exhibit six pulses of daily fish estimates eclipsing the 10,000 fish mark.

Smith-Root Counts

Daily alewife population estimates were documented in Black Creek from April 10, 2017 to May 20, 2017 (Table 3.5).

Table 3.5. Daily population estimate of spawning alewife in Black Creek. Estimates obtained through Smith-Root counts. New York, 2017.

Day	Total Fish	SE	df
4/18/17	14617	771.809	7
4/19/17	9417	319.207	7
4/20/17	3270	215.821	7
4/21/17	2922	246.110	7
4/24/17	14617	771.809	7
4/27/17	5762	1.080	7
4/28/17	8770	262.893	7
4/29/17	6685	81.417	7
4/30/17	9011	283.869	7
5/1/17	5650	8.668	7
5/2/17	2316	298.856	7
5/3/17	5032	62.458	7
5/4/17	4422	115.552	7
5/5/17	6801	91.513	7
5/10/17	2473	285.191	7
5/11/17	6448	60.789	7
5/12/17	6181	37.549	7
5/13/17	10114	379.873	7
5/17/17	428	463.185	7
5/18/17	33	497.565	7
5/19/17	1058	408.351	7
5/20/17	464	460.0516	7

April 18, April 24, and May 13 of the 2017 sampling season were marked by alewife estimates eclipsing the 10,000 fish mark. A daily average of 5,750 fish was realized over the course of these observed dates.

Chapter Three Discussion

In Table 3.1 we see that the mean number of river herring eggs per gravid female does not appear to be associated with fish distance from the Battery in Manhattan (New York) or conversely the Federal Dam in Troy (New York). The mean number of alewife eggs procured from post-mortem ovary analysis was greater than the mean number of blueback herring eggs over all sites of collection. No blueback herring were collected via haul seine at Black Creek, and Kingston. The majority of fish collected during sampling efforts in the Hudson River main stem were alewife at 111 fish.

Previous fecundity studies have measured the standing egg crop of blueback herring against fork length (mm), and it is useful to compare our total length based calculations with the literature. When standardized to a female of 265mm in total length, the standing egg crop (blueback herring) of our study was noted at 86,429 eggs. In a 2003 study of blueback herring fecundity in the Hudson and Mohawk Rivers (New York), 98,870 eggs were realized at a 265mm fork length (Limburg and Blackburn, 2003). Limburg and Blackburn (2003) note possible gear bias as gill nets were employed to capture fish and possible age classes may have been excluded. Jessop, similarly in 1993, found a mean egg crop ranging from 169,700-194,800 eggs in Canadian waters. Our standing egg crop estimates were most similar to the Limburg and Blackburn findings, though ours are lower when accounting for our standardization to total length (mm) as opposed to fork length (mm), and also because of haul seine collection methods.

In accounting for alewife fecundity to length schedules, Lake and Schmidt realized a standing egg crop of 72,000 eggs per 275.1mm (total length) long female in the Quassaic Creek tributary of the Hudson River (Lake and Schmidt, 1998). When standardized to an alewife with a total length of 275.1mm, the standing egg crop in our study was quite higher at 110,337 eggs.

Though spent fish were also eliminated from the Lake and Schmidt analysis, only “large” eggs were counted, gill nets were used for capture, and counting methods are assumed to be manual (Lake and Schmidt, 1998). This may explain some of the discrepancy between standing egg crop findings.

Total ovary weight was the best indicator of river herring standing egg crop as it showed the strongest association (positive) regardless of alewife or blueback species. Additionally, the Fulton condition factors appear to decrease as the river mile sampled extends northward for blueback herring. A fish would seemingly devote more resources to gonadal development the further they travel into the system (which is the case for blueback herring), however, this is not the case for alewife.

A general decline was noted in the number of eggs and larva procured from drift net sampling over the course of the river herring run. The multimodal peaks are not as conspicuous, but a slightly oscillating pattern is present. The mean number of river herring eggs (assumed alewife) collected per 300s (5 minute) drift in Black Creek was 8,951 eggs and 8,630 eggs in the Fall Kill. This is in juxtaposition with our egg mat findings illustrating greater mean egg counts in the Fall Kill. I believe this is due to the shallower bathymetric profile of the Fall Kill, where some of the drift nets were partially set above water. Additionally, this could be due to debris composition and quantity in the Fall Kill, as well as varying velocities.

Previous research has attempted to extrapolate the number of river herring eggs per volume of drift for the entire volume of a Hudson River tributary, and it is worth comparing results (Lake and Schmidt, 1998). The total number of eggs extrapolated from drift net samples to the volume of Quassaic Creek was estimated at 38.0 million eggs from March 28, 1997 to June 10, 1997 (Lake and Schmidt, 1998). In Black Creek we again estimated 10.2 million eggs from April 17, 2017 to June 5, 2017 and 15.2 million eggs for the Fall Kill. With the 25 day duration discrepancy accounted for, these numbers appear to be in a similar realm of reasonable expectation.

Daily population estimates of spawning river herring derived from Smith-Root and visual counts shared overlapping dates from April 18, 2017 to May 20, 2017 (Figure 3.10).

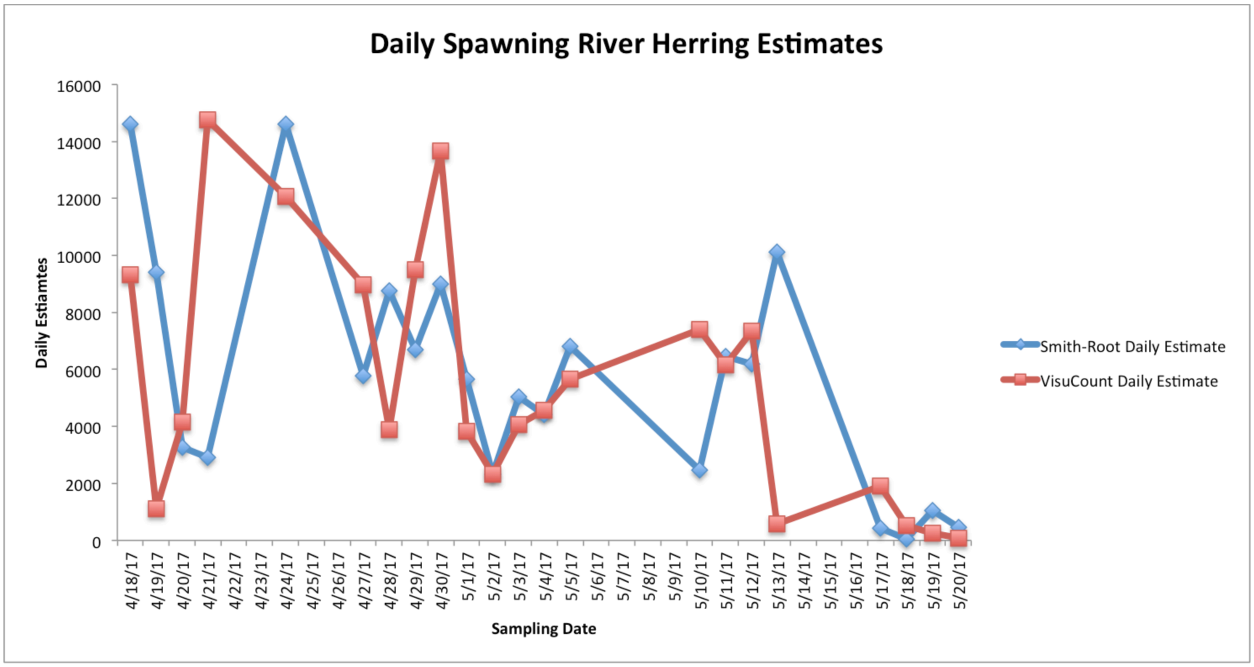

Fig. 3.10. Marked scatterplot of daily spawning river herring estimates for Black Creek. The estimates obtained from Smith-Root counts are compared with VisuCount based estimates. New York, 2017.

These two methods visually share a similar pattern, however, a daily lag is present. The lag may be attributed to a delay in the output reading of the Delta Vision camera. A two-sample t-test was performed to compare the means between these two spawning river herring population estimates. Fisher's F-test was first performed and revealed homogeneity in variance as the associated p-value of 0.80 was greater than 0.05, and the subsequent computed F-value of 0.895 was less than the tabulated F-value of 2.084. With variances approximately equal, the two-sample t-test revealed a p-value of 0.877 ($p > 0.05$) so we conclude that the means of these two groups are similar within the 95% confidence interval. The mean of the Smith-Root values was 5,750 fish and the mean of the VisuCount values was 5,550 fish. The confidence intervals were ultimately bootstrapped with 10,000 replicates (Table 3.6).

Table 3.6. Smith-Root and VisuCount mean daily river herring estimates with bootstrapped 95% confidence intervals for Black Creek. New York, 2017.

Method	n	Mean	Boot CI Lower	Boot CI Upper
Smith-Root	22	5750	4210	7640
Visual	22	5550	3920	7510

126,500 total spawning alewife, 95% CI [92,620, 168,080] were estimated from Smith-Root Counts and 122,100 total spawning alewife, 95% CI [86,240, 165,220] were estimated from visual counts in Black Creek over the sampling duration.

Video counts were also recorded in the Fall Kill from April 15, 2017 to May 19, 2017 (Figure 3.11).

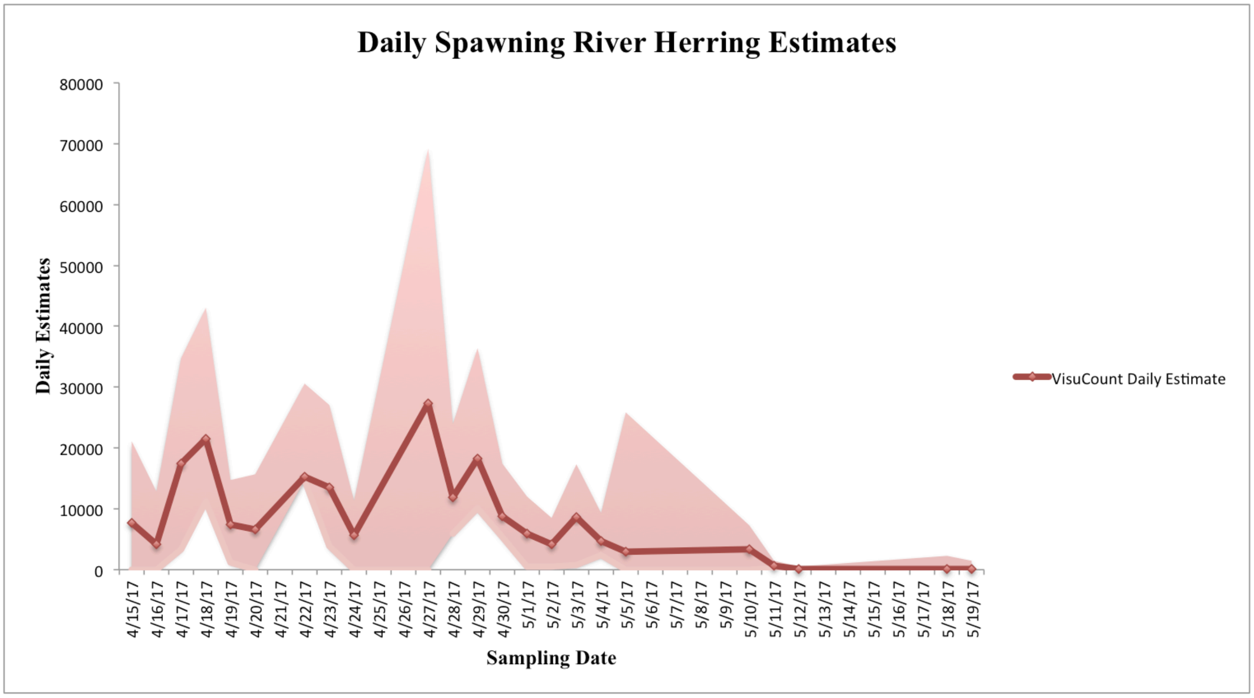

Fig. 3.11. Marked scatterplot of daily spawning river herring estimates for the Fall Kill within a 95% confidence interval. Estimates were obtained from visual counts. New York, 2017.

196,374 total spawning alewife, 95% CI [74,497, 318,251] were estimated from April 15, 2017 to May 19, 2017. The mean estimate for spawning alewife over the same duration was 8,538 fish, 95% CI [3,345, 13,730].

In assuming that the ratio of female alewife to male alewife is 50:50, based on DEC field sampling observations in Black Creek from 2013-2016, we can halve the daily alewife estimates and multiply them by the standing egg crop to obtain alewife eggs produced per day. In standardizing the mean alewife standing egg crop to mean total ovary weight, we take the value of 121,021 eggs and multiply it by 2,775 female alewife estimated daily in Black Creek to obtain a daily production value of 335.8 million alewife eggs, 95% CI [237.2 million, 454.4 million]. Similarly we estimate a daily production value of 516.6 million alewife eggs, 95% CI [202.3 million, 830.8 million] per 4,269 females in the Fall Kill.

Estimated daily spawning alewife obtained from VisuCount could also theoretically be compared against estimates obtained from drift net sampling and fecundity. A total of 209,167 drifting alewife eggs were estimated daily per the entire volume of Black Creek. We can divide this mean number of drifting eggs by the mean number of eggs carried within a standardized alewife ovary, to obtain a daily estimate of female alewife, however this value would insinuate one to two spawning females per day. Our mean daily estimate of adult females (obtained from Smith-Root and visual counts) are significantly higher than a previous study in the Quassaic Creek where 2,248 females were estimated over the course of an entire run (Lake and Schmidt, 1998). This leads me to believe that drift net sampling, when extrapolated to stream volume at large, results in an under estimation of egg productivity within the scope of our study. Egg predation, and natural mortality rates should be explored further in future studies to potentially develop a correction factor for explaining actualized egg productivity in a system.

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Conclusion and Justification

Anadromous river herring provide for important recreational and commercial fisheries in the Hudson River. Regulations will continually evolve to match the dynamic nature of river herring spawning runs as a function of a sustainable fishery. The development of a long-term stock assessment program will have the two-fold effect of keeping ASMFC member states continually in compliance (open fishery), and will also improve the accuracy of stock assessment modeling through the utilization of established (long term) prior inputs. Quantifying the spawning abundance, fecundity, egg productivity, and spatio-temporal distribution in particular, will help decision makers set appropriate fishing management regulations in accordance with the presence or absence of river herring in a given system. The incorporation of abiotic factors into spawning dynamics research will ultimately help shape habitat management. Being able to improve, or more importantly preserve spawning habitat, can only reinforce healthy river herring spawning numbers and healthy spawning behavior. In the discussion of barrier manipulation (natural and/or artificial), knowing the spawning tendencies, abundance, and distribution of river herring can help reaffirm or refute the added benefits and/or costs of barrier manipulation and supplemental fish passage. In regards to future data collection, the use of PIT tags, external t-bar anchor tags, and egg mats will offer a new means for collecting the aforementioned data, and also a new means for cross referencing multiple stock assessment methods (Normandeau Associates, Inc., 2007).

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Appendix A

Generalized Additive Models

Generalized additive models (GAM's) were also explored for the modeling of river herring egg abundance. They may also be applied in the case of negative binomial and Poisson distributions, and offer some flexibility for curve fitting as GAM's are non-parametric in nature. This class of models can address issues of non-linearity that are often encountered in applied data analysis (Hastie and Tibshirani, 2006). With GAM's, a smoothing function is applied to covariates and the basic configuration of this model is

$$g(\mu_i) = \mathbf{X}_i^* \boldsymbol{\theta} + f_1(x_{1i}) + f_2(x_{2i}) + f_3(x_{3i}, x_{4i}) + \ldots$$

$$\mu_i \equiv E(Y_i) \text{ and } Y_i \sim \text{ a given exponential family of distribution}$$

where Y_i is the response variable, $\mathbf{X}_i^*$ is a model matrix row for exclusively parametric model items, $\boldsymbol{\theta}$ is the analogous parameter vector, and f_j are a series of smoothing functions applied over the predictor covariates. By choosing a basis, and defining the space of functions of which the smoothing term is an element, f can be estimated. A cubic spline is a common basis function, and the degree of smoothness can be controlled in R with penalized regression splines (Wood, 2017).

The best fit GAM (negative binomial family of distribution) explaining river herring abundance for both Black Creek and the Fall Kill combined included water velocity, moon phase, and water temperature as abiotic predictor covariates (Figure A.1).

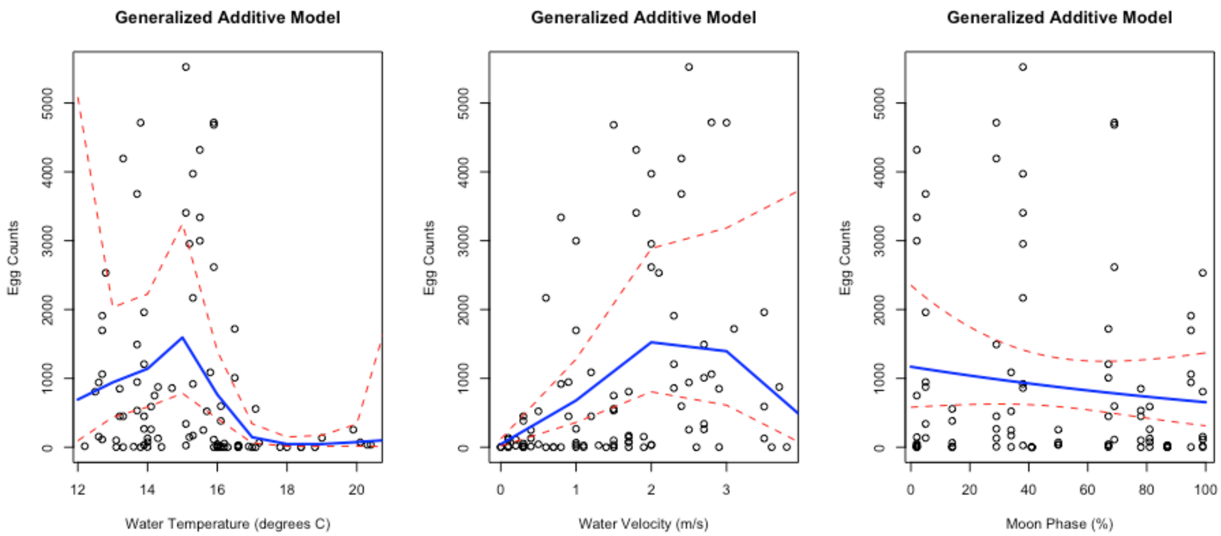

Fig. A.1. Estimated river herring egg mat egg counts per $58.1cm^2$ subsample in both Black Creek and the Fall Kill combined, fit with generalized additive model lines. Water temperature, water velocity and moon phase covariates are presented side-by-side. New York, 2017.

Statistically, this is expressed with an adjusted R^2 value of 0.234, 41.3% of the deviance explained on a sample size of 93, and an AIC of 1267.371 (Table A.1).

Table A.1. Generalized additive model explored at both Black Creek and the Fall Kill tributaries combined. The predictor variables from the best fit generalized additive model are displayed in the table below. New York, 2017.

Variable	edf	Ref. df	Chi. sq	p-value	Sig. Code
s(Water Velocity)	2.421	3.003	34.66	<0.001	***
s(Moon Phase)	2.531	3.072	10.38	0.017	*
s(Water Temperature)	6.051	7.147	52.33	<0.001	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

In reference to Black Creek exclusively, the GAM (negative binomial) that included water velocity, Julian date set, and water temperature for predictor variables had the lowest AIC at 585.318. This best fit GAM is presented graphically with each significant predictor variable set against river herring egg counts per $58.1cm^2$ subsample (Figure A.2).

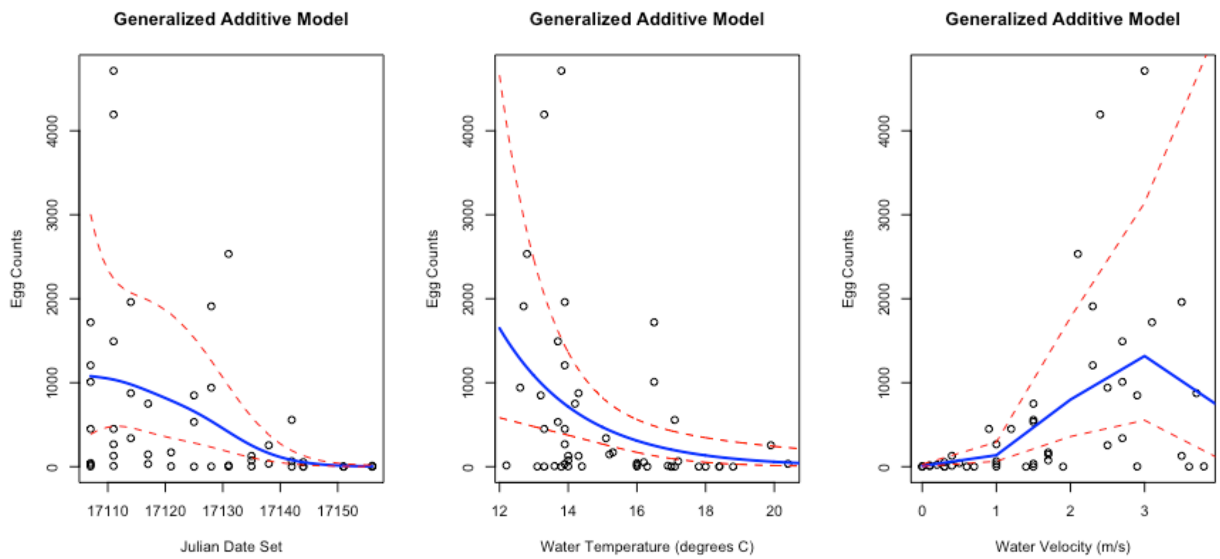

Fig. A.2. Estimated river herring egg mat egg counts per 58.1cm^2 subsample in Black Creek, fit with generalized additive model lines. Julian date set, water temperature, and water velocity covariates are presented side-by-side. New York, 2017.

The statistical summary of this GAM is exhibited with an adjusted R^2 value of 0.498, with 51.5% of the deviance explained on a sample size of 48 (Table A.2).

Table A.2. Generalized additive model explored at Black Creek. The predictor variables from the best fit generalized additive model are displayed in the table below. New York, 2017.

Variable	edf	Ref. df	Chi. sq	p-value	Sig. Code
s(Water Velocity)	2.74	3.384	46.437	<0.001	***
s(Julian Date Set)	1.00	1.001	5.365	0.021	*
s(Water Temperature)	1.00	1.000	3.342	0.068	.

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

A generalize additive model (Poisson) containing the covariates pH, water velocity and moon phase proved to be the best model for estimating river herring egg abundance in the Fall Kill exclusively, with an AIC of 283.783. This best fitting GAM is presented graphically with each significant predictor variable set against river herring egg counts per 58.1cm^2 subsample (Figure A.3).

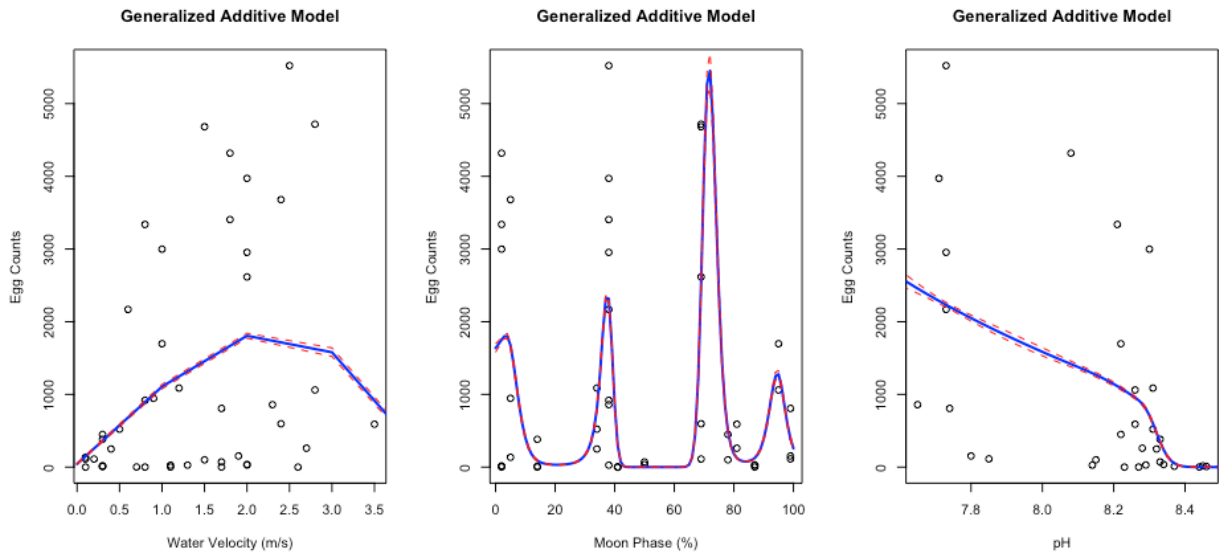

Fig. A.3. Estimated river herring egg mat egg counts per $58.1cm^2$ subsample in the Fall Kill, fit with generalized additive model lines. Velocity, moon phase, and pH covariates are presented side-by-side. New York, 2017.

The statistical summary of this GAM produced an adjusted R^2 value of 1, with 100% of the deviance explained on a sample size of 31 (Table A.3).

Table A.3. Generalized additive model explored at the Fall Kill. The predictor variables from the best fit generalized additive model are displayed in the table below. New York, 2017.

Variable	edf	Ref. df	Chi. sq	p-value	Sig. Code
s(pH)	9.000	9.000	1323	<0.001	***
s(Moon Phase)	8.035	8.121	2546	<0.001	***
s(Water Velocity)	9.000	9.000	2604	<0.001	***

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

The GAM’s in our study may be useful for estimating egg counts at a specific snapshot in time with a limited data set, however, I believe that the GAM’s in our study tend to over fit the generally noisy data. Perhaps the smoothing parameters could be adjusted going forward as future data reveals potential trends.

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Appendix B

In-stream Duration and Spawning Turnover Rate

A PIT tag reader was installed adjacent to the Smith-Root SR-1601 fish counter in Black Creek, and fish were tagged in an attempt to record in-stream duration and the resulting spawning turnover rate. Initial power calculations (alpha = 0.05, probability of detection = 20%) were conducted, and a proposed range of 400-600 spawning river herring was realized for PIT tagging from April 17, 2017 to June 05, 2017.

Individuals were collected with dip nets at the Hudson River main stem confluence. Fish, that received PIT tags and were successfully detected by the PIT tag reader, were considered as initiating their spawning behavior. Fish that were detected dropping out of a tributary had their measured spawning duration momentarily suspended until their re-entry was observed (unless it was indeed their final exit from the system). A fish that was initially detected and whom ultimately failed to be detected exiting a tributary was considered null and was excluded from study. The resulting amount of time a tagged individual spent in the study area of Black Creek was compiled and recorded.

A total of 63 river herring were tagged over the course of two sampling days (April 28, 2017 and May 3, 2017). Of those 63 fish, 29 fish were detected by the PIT tag antenna. Detection interference between the Smith-Root SR-1601 and the PIT tag antenna led to a poor estimation of survey life duration. An inordinate amount of fish were detected entering the survey area relative to the number existing the system.

The in-stream spawning duration was intended to supplement the assessment of multi-modal spawning behavior. As an accompaniment to egg and larval data collection, PIT tagging would allow for further gear feasibility study and would provide insight into peak spawning periods for future sampling efforts. A double counting correction factor may also be conceivable. The lack of PIT tags administered and detection interference between the Smith-Root SR-1601 fish counter and the PIT tag antenna, lead to collected data of little remark. Future population dynamics study would undoubtedly benefit from in-stream duration and spawning turnover rate related data.

Appendix C

Esopus Creek and Rondout Creek

Spawning river herring abundance, and turnover rate (escapement), was modeled for Esopus Creek and Rondout Creek. Schmidt and Cooper (1996) chose to investigate tributaries based on size, with larger bodies being deemed more fruitful for data collection. The Esopus Creek and Rondout Creek are classified as such, are high priority tributaries, and were selected for additional site assessment (Schmidt and Cooper, 1996).

Esopus Creek (~86.2 meters wide at rt 9W) and Rondout Creek (~114.0 meters wide at rt 9W) contained ample space for boat electrofishing and transecting operations while still maintaining choke points for mark-recapture study. The first barrier of the Esopus Creek is the Diamond Mill Paper Company Dam (downstream of the rt. 9W bridge) in Saugerties (2.03 km upstream of the Hudson River interface) (Schmidt and Cooper, 1996). The first barrier of the Rondout Creek is the Eddyville Dam (4 km upstream of the rt. 213 bridge, and 5 km upstream of the Hudson River interface)(Schmidt and Cooper, 1996). In order to measure the relative spawning abundance and spawning turnover rate of river herring in the larger Esopus Creek and Rondout Creek, methods differing from those employed on Black Creek and the Fall Kill were conceived.

Due to the larger nature of these tributaries, and the expenditure required to execute useful spawning turnover rate studies, PIT tagging and acoustic tagging appeared to be less than feasible options. Trapezoidal approximation (depicted in the following model) was to be utilized to calculate spawning turnover rate, more as a function of survey life and the time fish spent in the survey area (Hilborn *et al*., 1999).

$$\text{AUC} = \sum_{i=2}^{n} (t_i - t_{i-1}) \frac{(x_i + x_{i-1})}{2}$$

Where AUC is the area calculated under the curve, t_i is the day of the year, x_i is the number of fish observed for the *i*th survey (English *et al.,* 1992, Bue *et al.,* 1998, and Hilborn *et al.,* 1999). This particular AUC is dependent on the assumption that the first and last day of the survey is marked by the presence of zero fish (Hilborn *et al.,* 1999). If the presence of fish on the first and/or last day of the survey are non-zero, then the following calculations should be noted.

$$AUC_{first} = \frac{x_1}{2}$$

and

$$AUC_{last} = \frac{x_{last} s}{2}$$

Where AUC_{first} is the area under the curve calculated for the first day of the survey, x_1 is the number of fish observed on the first day, AUC_{last} is the area under the curve calculated for the last day of the survey, x_{last} is the number of fish observed on the last day, and *s* is the survey-life (Hilborn *et al.,* 1999). Fish counts were observed in seven day intervals through boat electrofishing and netting (CPUE to be described later for abundance measurement). With the AUC calculated, the following equation was used to calculate the expected escapement.

$$\hat{E} = \frac{AUC}{s} v$$

Total expected escapement is represented by $\hat{E}$, where v is a correction for observer efficiency. An observational model could be used to account for this correction for observer efficiency (Hilborn *et al.*, 1999).

$$C_t = vN_t$$

An observer was to count the number of fish present at a particular time (x_t). The predicted counts of fish on day t (C_t) are assumed to be proportional to the number of fish alive in the stream (N_t), and scaled by observer efficiency (v) (Hilborn *et al.*, 1999).

In regards to abundance calculations in Esopus Creek and Rondout Creek, boat electrofishing (transects within each of the three pre-defined strata) were carried out in seven day intervals with an appropriately established CPUE (Harley *et al.*, 2001).

$$CPUE = \frac{C}{E} = q \times N$$

and

$$q = \frac{C/N}{E}$$

where C is catch, E is effort, q is catchability, and N is abundance (Harley *et al.*, 2001). In terms of our study, the CPUE was set as the number of fish collected per an ascribed transect area within each of the three strata. Captured fish were also to be marked for recapture (anchor FF-94 tags in different colors corresponding with a unique seven day interval) as a second reference (illustrated below).

$$N = \frac{M \times T}{R}$$

Where N is the total population size, M is the number of fish marked initially, R is the number of fish recaptured, and T is the total number of fish captured in the second sample. This method assumes that the population is closed, there is equal chance of capture, marking and recapture periods must be separated by a sufficient amount of time, and that herring maintained their tags.

Few fish were captured along the majority of transects throughout Esopus Creek and Rondout Creek. Fewer fish still were initially marked through Floy anchor FF-94 tags and recaptured. Interesting enough, the bulk of fish captured through boat electrofishing were found congregating near each tributary's respective first barrier to anadromous fish migration. This may prove useful for locating the greatest abundance of fish and for targeting specific populations within larger tributaries (when using electro fishing based methods).

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